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CONTENTS OF VOLUME XXXIX

NUMBER 1

	PAGE
Isostasy from the Geological Point of View. Rollin T. Chamberlin	1
The Appalachian Structural Front. Paul H. Price	24
The Peorian Loess and the Classification of the Glacial Drift Sheets of the Mississippi Valley. Morris M. Leighton	45
Classification of Igneous Rock Series. M. A. Peacock	54
Genesis of the Anthophyllite Deposits near Kamiah, Idaho. Alfred L. Anderson	68
Cooke's Correlation of Coastal Terraces: A Discussion. Richard Foster Flint	82
Reviews	91
Publications Received	96

NUMBER 2

A Structure Section across the Canadian Rockies. Percy E. Raymond and Bradford Willard	97
Structural Geology of Northeastern Oklahoma. Sidney Powers	117
Desert Plains. Eliot Blackwelder	133
Studies on the Morphology of the Heterostraci. H. C. Stetson	141
The Method of Multiple Working Hypotheses. T. C. Chamberlin	155
Reviews	166
Publications Received	192

NUMBER 3

Revision of the Payette and Idaho Formations. Virgil R. D. Kirkham	193
The Adirondack Magmatic Stem. A. F. Buddington	240
The Isostasy of the Uinta Mountains. Andrew C. Lawson	264
Paleozoic Cherts of West-Central Virginia. Herbert P. Woodward	277
Granite Intrusions in the Huronian Formations of Northern Michigan. Carl A. Lamey	288
Reviews	296
Attention of Mineral Collectors	304

NUMBER 4

PAGE

A Study of Sandstone Members of the Jefferson City and Cotter Formations at Rolla, Missouri. Oliver R. Grawe and James S. Cullison 305

Anorthosite in Los Angeles County, California. William J. Miller 331

Glacial Troughs of the Continental Shelves. Francis P. Shepard . 345

Stratigraphy of the Ordovician Hounsfield Metabentonite. G. Marshall Kay 361

Origin of the Pebble Band on Iowan Till. George F. Kay 377

Loess, Pebble Bands, and Boulders from Glacial Outwash of the Greenland Continental Glacier. William H. Hobbs 381

Warping of Appalachian Peneplains. Karl Ver Steeg 386

Reviews 393

Publications Received 400

NUMBER 5

On the Terms Eutectic, Cotectic, Peritectic, Anchi-eutectic, Anchi-cotectic, etc., and Their Importance in Petrogenesis. Johan H. L. Vogt 401

Petrography of the Beach Sands of Southern Lake Michigan. F. J. Pettijohn 432

Snake River Downwarp. Virgil R. D. Kirkham 456

Reviews 487

NUMBER 6

A Theory of Appalachian Geomorphic Evolution. Douglas Johnson 497

Fishes of the Jefferson Formation of Utah. E. B. Branson and M. G. Mehl 509

The Structure of the Sierra Maestra near Santiago de Cuba. Stephen Taber 532

The Problem of the Bartlett Trough. Stephen Taber 558

Igneous Geology of Southwestern Idaho. Virgil R. D. Kirkham . 564

Another Kansas Meteorite. H. H. Nininger and Garrett A. Muilenburg 592

Discussion of "A Structure Section across the Canadian Rockies" by Percy E. Raymond and Bradford Willard. Ralph L. Rutherford and Percy E. Raymond 597

Reviews 601

NUMBER 7

PAGE

THE WANING OF THE LAST CONTINENTAL GLACIER IN DENMARK AS ILLUSTRATED BY VARVED CLAY AND ESKERS. S. A. Andersen . . . 609

THE APPLICATION OF MECHANICAL STRUCTURAL PRINCIPLES IN THE WESTERN ALPS. Andrew Leith 625

SOLUTION DEPRESSIONS IN SANDY SEDIMENTS OF THE COASTAL PLAIN IN SOUTH CAROLINA. Laurence L. Smith 641

RECENT STREAM INTERCISION. Amy M. Thwaites 653

"SEINE" OR "COUTCHICHING" BY J. E. HAWLEY: A DISCUSSION. James E. Gill and J. E. Hawley 655

ALGAE AND ALGAL BEDS IN THE BELT SERIES OF GLACIER NATIONAL PARK. Carroll Lane Fenton and Mildred Adams Fenton 670

REVIEWS 687

PUBLICATIONS RECEIVED 696

NUMBER 8

THE PRE-CARBONIFEROUS EXOTIC BOULDERS IN THE SO-CALLED CANEY SHALE IN THE NORTHWESTERN FRONT OF THE OUACHITA MOUNTAINS OF OKLAHOMA. W. A. J. M. van Waterschoot van der Gracht . . 697

SPONTANEOUS ROCK EXPANSION. George W. Bain 715

INCLUSIONS AND FOLIATION OF THE HARNEY PEAK GRANITE, BLACK HILLS, SOUTH DAKOTA. Robert Balk 736

PENEPLAINS OF THE APPALACHIAN PLATEAU. Harry M. Fridley and John P. Nölting, Jr. 749

RICHARD ALEXANDER FULLERTON PENROSE, JR. 1863–1931. Rollin T. Chamberlin 756

REVIEWS 761

INDEX TO VOLUME XXXIX 763

VOLUME XXXIX NUMBER 1

THE
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ISOSTASY FROM THE GEOLOGICAL POINT OF VIEW[1]

ROLLIN T. CHAMBERLIN
University of Chicago

ABSTRACT

Some of the outstanding geologic facts which have to be taken into account in a consideration of isostasy are enumerated. Mountain building, peneplanation, geosynclines, etc., are considered from the point of view of both geologic deductions and the isostatic theory. It is concluded that no single type of compensation or uniform depth of compensation meets the facts. The real test of the isostatic theory seems to lie in the limited regions of high relief. An attempt is made to show how geologic processes may operate to produce folded mountain ranges exhibiting the observed geologic phenomena and at the same time make it possible to satisfy the requirements of the geodetic determinations. Isostatic forces are in the whole equation of mountain-building forces, and play their appropriate part, but that part is secondary and subordinate.

INTRODUCTION

Nearly fifty years have elapsed since Dutton introduced the word "isostasy" to designate a postulated condition of equilibrium in the outer portion of the earth shell. He was building on the earlier work of Pratt and Airy in India dating from 1855. During this long stretch of time geodetic evidence has slowly accumulated and has now led many to accept an isostatic condition of the earth shell as a demonstrated fact. On the other hand, various geologic observations and deductions, which the geologist regards as established facts, seem inconsistent with the isostatic theory as now applied by its leading advocates. To the geologist the recognized geologic facts, which he can understand and appreciate, are vastly more convincing

[1] Presented before the Geological Society of Washington, April 30, 1930.

than mathematical interpretations based upon assumptions, some of which he does not understand, and others of which seem to him clearly at variance with the actual earth conditions. Though the mathematical mill grinds with precision, the mill has been fed so commonly with defective assumptions and untruths in past application to geological problems that the grist has often proved more deleterious than beneficial. Past experience justifies the geologist in viewing with caution and skepticism mathematical deductions which seem inconsistent with field observations logically interpreted. Isostasy after all is a geological problem. What are the geologic factors and facts that enter into this problem?

GEOLOGIC ASPECTS OF MOUNTAIN BUILDING

Some of the geologic facts that have to be taken into account are as follows:

1. Folding into mountain ranges occurs, in general, where weak and light sediments have previously accumulated to exceptional thickness.

2. Low-angle overthrusts with horizontal displacement up to 20 miles, or even more, are a characteristic and dominant structure of the more strongly folded mountain systems. Any theory of earth deformation which runs counter to big overthrusts, or does not allow them full place, must go down in defeat.

3. The faulting, folding, and schistosity exhibited in many mountain ranges involve much crustal shortening—200 miles for the full breadth of the Appalachian belt (Keith), 125–185 miles for the Alps (Heim), etc. The cleavage, schistosity, and extraordinary crumpling in the pre-Cambrian, and in many younger rocks in mountain ranges, give the geologist the picture of intense horizontal compression. Broad belts of earth crust have been squeezed into strips now less than half their former width. That is the most outstanding characteristic of strong mountain building of the fold type. Whatever else we may have in the picture, we must have that.

4. The horizontal squeezing of broad belts of the earth's surface into deformed strips of half their former width forces material either upward, or downward, or both. Near the surface, relief is presumably easiest upward. In the portion which we see there has been

more upward folding than downward. Keith has shown that the Appalachian folding was characterized less by depression of the synclines than by rise of the anticlines.[1]

The rise of growing anticlines may be seen in the East Indies. Some geologists, emphasizing the submerged state of considerable portions of these young foldings, have implied that the process of folding itself causes little elevation. But in the East Indies, sea level is not the proper level of reference; rather is it the floor of the ocean, some 15,000 feet below, above which the folds have risen into lofty chains, whose highest portions now constitute islands.

UPWARD MOVEMENT

The view that the principal elevation of folded mountain belts does not occur at the time of the folding and as a part of the process, but comes instead after a long interval of erosion (peneplanation), seems to the writer a confusion of ideas. Let us use the Appalachians as an illustration. Folded in the closing stages of the Paleozoic, they were essentially baseleveled during the Mesozoic, and have since been raised regionally in several episodes of uplift. The present elevation of the Appalachian ridges above sea level is, of course, the result of the Cenozoic uplifting, which dynamically was of a different sort from the late Paleozoic folding and faulting. This later uplifting was very real and has long been recognized, but in what way does the fact that there was uplift at several times during the Cenozoic constitute evidence against uplift as a part of the Permian Appalachian revolution? Cenozoic uplift seems to the writer to have no necessary bearing on what happened at the close of the Paleozoic.

On the contrary, it is easy to show that the Permian Appalachian revolution did produce mountains higher than the present Appalachians. Examine the western flanks of this mountain system. In Pennsylvania, where folding predominates, the strata of the Cumberland Plateau to the west of the mountains exhibit some waviness, but in general do not depart greatly from horizontality. The surface strata are mostly of Pennsylvanian age. At the Appalachian structural front the strata turn sharply upward to verticality in the west-

[1] Arthur Keith, "Outlines of Appalachian Structure," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 318.

ern limb of a great anticline. East of Tyrone the bending of this anticline has brought Middle Ordovician beds up level with the Pennsylvanian beds west of the strongly folded tract. On a reasonable reconstruction of the fold the crest of this anticline, except for erosion, reaches a height of over 20,000 feet above the lands to the west. Dissection of the anticline accompanied the rise, but isolated remnants must have remained as lofty peaks for a long time.

In Tennessee, where thrust faulting predominates, the Briceville folio gives some very characteristic sections (see Fig. 1). What is more striking than the slice-faulted, strongly deformed Cambro-Ordovician beds of the Appalachian tract sharply separated by a boundary fault from almost perfectly horizontal Pennsylvanian beds in the adjoining Cumberland Plateau? The undeformed area of

FIG. 1.—Section across western portion of the deformed Appalachian belt and eastern portion of the undeformed Cumberland Plateau adjacent. From Briceville, Tennessee, folio, U.S.G.S. Cambrian and Ordovician (*Sk* and *Sc*) formations in the deformed right half of the section; flat-lying Pennsylvanian formations in the left half. A reconstruction of the fault blocks as they were before peneplanation requires their rise into high mountains developed directly by the folding and faulting processes, quite irrespective of later vertical uplifts affecting the whole region.

horizontal Pennsylvanian strata still maintains its original attitude. Hence we may use the top of the sedimentary column here as a datum plane from which to estimate the upward movement of the deformed mountain belt. The Cumberland Plateau area is not thought to have sunk below sea level after the beginning of the Appalachian revolution, and the magnitude of the mountainous rise is indicated by the throw of the thrust faults. Today, however, owing to erosion, this portion of the Appalachian folded belt (Appalachian Valley) is actually at a lesser elevation than the adjoining area of flat-lying strata (Cumberland Plateau) to the west. Since peneplanation of the old mountains the whole general region (folded and unfolded areas alike) has been uplifted. Differential erosion has developed the present topographic relief.

DOWNWARD MOVEMENT

The upward bulging of a folded tract in the process of folding is observed in the upper portion of the deformed belt, and has already

been treated quantitatively for the Pennsylvania Appalachians.[1] In addition, there may be also some downward movement of the compressed rock material in the deeper portion of the deformed block. Its quantitative importance is more difficult of determination than is that of the upward bulge, but Heim strongly champions the view that the geosynclinal sediments in the deeper portions of the central Alps now lie, in their folded condition, at much greater depths below the surface than they did in the geosynclinal trough just previous to the beginning of the folding.[2] Kossmat,[3] Born,[4] Lawson,[5] and many others see evidence for downward movement of material in the lower reaches of a squeezed mountain belt.

ISOSTASY AS A MOUNTAIN BUILDER

The keynote of isostasy is a working toward equilibrium. Isostasy is not a process which upsets equilibrium, but one which restores it. In the attainment of equilibrium the long, light columns and the short, heavy columns of the isostatic conception tend to become more and more nearly equal in specific gravity, and consequently height, as time goes on (Fig. 2). In short, the system, by itself, runs down. Differences in specific gravity and topographic relief become less and less until a static condition of equilibrium is reached. Relief on the globe, following the purely isostatic view, should have been greatest in the Archeozoic, less in the Proterozoic, still less in the Paleozoic, and least at the present time. Yet today is a time of exceptional relief in the history of the globe.

During many geologic periods shallow epicontinental seas have spread widely over the continents. Middle Ordovician times, for example, witnessed shallow marine waters spread over some 60 per cent of North America. The characteristic limestones of that epoch testify to the clarity of those seas and the paucity of high land to muddy them. At various later times, as at present, the continents have become emergent and high standing. One may also ask: What

[1] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. XVIII (1910), pp. 228–51.

[2] Albert Heim, *Geologie der Schweiz*, Vol. II (1922), pp. 51–52, 878–89.

[3] Franz Kossmat, *Geologische Rundschau*, Vol. XII (1921), p. 170.

[4] A. Born, *Isostasie und Schweremessung* (Berlin, 1923), pp. 70–76.

[5] Andrew C. Lawson, "The Geological Implications of Isostasy," *Bull. Nat. Research Council*, Vol. VIII, No. 46 (1924), pp. 10–13.

could have given the earth surface originally the pronounced relief required by this hypothesis if isostatic processes, or processes working toward equilibrium, are the dominant ones?

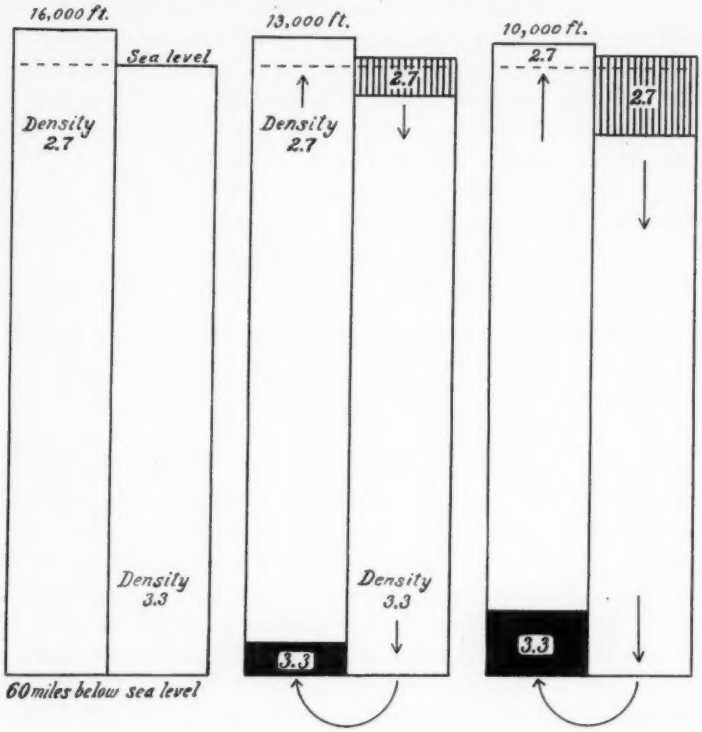

FIG. 2.—Diagram to illustrate column 16,000 feet above sea level reduced by erosion to 10,000 feet above sea level, in accordance with the isostatic theory. To lower the top of the column 6,000 feet, on the basis assumed, requires the erosion of 33,000 feet of rock which, in turn, causes the column to rise 27,000 feet to preserve equilibrium. In the case selected the eroded material is deposited on an adjoining sea-level column of equal surface area which receives 33,000 feet of sediment and is depressed thereby 27,000 feet. If the eroded material were distributed over a larger area, that area would be depressed correspondingly less by the weighting.

REGIONAL UPLIFTS

I wish to call attention also to regions which have been mountainous and which have since been baseleveled. With the attainment of

the baseleveled condition, no topographic relief remains to be compensated, and the cycle has run its course. The numerous flat erosion surfaces of the past have indicated nearly stable conditions for long periods of time. If stable, and in a state of balance, why should they not have remained stable for ever after, if isostatic forces are the dominant ones? Actually, however, peneplaned folded areas commonly have been uplifted in later times. We find peneplain remnants on the tops of many present mountain ranges, such as the Appalachians, portions of the Rockies, Andes, etc. The old mountain areas after peneplanation have gone up again in many cases. What has put them up again?

Expansion of material in the mountain column is a working hypothesis. Changes of temperature and chemical and physical changes have been suggested. During the accumulation of sediments in a sinking geosyncline a rise of temperature of the sediments should accompany their burial. For a depression of the geosynclinal belt to the extent of 30,000 feet a rise of temperature of perhaps 300° C. may be expected. If the underlying material of the rock column had a cubical coefficient of expansion of 0.000038 per degree Centigrade and was raised 300° C. in temperature, we should expect an elevation of the surface of only about 3,500 feet if the expanding column extended to a depth of 60 miles.[1]

Much of this heating and expansion should have occurred during the sedimentary filling of the geosyncline which, in the case of the Appalachians, occupied nearly the whole of Paleozoic time. After the Appalachian revolution at the close of the Paleozoic, denudation succeeded burial, inaugurating the reverse conditions of cooling and contracting which prevailed throughout the Mesozoic. Though allowing for lag in the heating process, not much Cenozoic uplift can be attributed to this type of thermal expansion.

Bowie has suggested the possibility of more potent expansion from chemical reactions or physical changes, of some as yet unknown sort, consequent upon changes in temperature and pressure.[2] But the

[1] William Bowie, "Theory of Isostasy—a Geological Problem," *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), pp. 283–85.

[2] William Bowie, "Isostatic Investigations and Data for Gravity Stations in the United States Established since 1915," *U.S. Coast and Geod. Surv. Spec. Pub. 99* (1924), pp. 42–46.

range of temperature, 300° C., is not great, nor does that of the pressure loom very large relatively. Furthermore, such postulated changes should have been going on during all the slow sedimentation of the Paleozoic and the protracted denudation of the Mesozoic. Are density changes of this sort in the thin superficial shell likely to have been great enough, after the Kittatinny peneplain stage, to cause the observed post-Cretaceous uplifts of the Appalachians? I think not. Much greater uplifts are recorded in the Andes, Tibet, and elsewhere.

Can the uplift be explained by lighter rock coming into the mountain column by intrusion from elsewhere? It is not apparent where lighter rock can come from. The mountain column is the light-rock column. If the Appalachian region during the Kittatinny peneplain state were in a state of nearly perfect isostatic equilibrium, as isostasists imply, there would be no adequate forces, on the purely isostatic hypothesis, to cause such intrusions. Isostasy cannot be the whole story.

HORIZONTAL MOVEMENTS

The face of the earth displays linear mountain systems of great length. The great Cordilleran chains parallel the western margins of both North and South America, and continue also in Siberia and Antarctica, amounting in all to about a third of the circumference of the globe. The east and west Alpine chains are a nearly continuous belt including the Pyrenees, Alps, Carpathians, Caucasus, Himalayas, and onward to the Pacific Ocean. These are not mere local manifestations arising from the balancing of small individual blocks. The wrinkling of such long strips of the globe represents world-deformation. Diastrophism of this sort calls for the world-map.

These folded chains are mostly on land. But the East Indies have been folded and faulted up from the sea floor; likewise the Dolphin Ridge, or mid-Atlantic swell which strikes up a median sinuous course between the curving American shores on one side and those of Eur-Africa on the other. Schistose rocks testify to the folded nature of this deep-sea ridge.[1] Here appeal can hardly be made to

[1] H. S. Washington, "The Origin of the Mid-Atlantic Ridge," *Jour. Maryland Acad. Sci.*, Vol. I (1930), pp. 20–29.

the transfer of material by erosion and sedimentation as in the orthodox way of making mountains by isostatic adjustment.

The inadequacy of isostatic adjustment to occasion crustal shortening on the scale observed is, perhaps, the greatest shortcoming of the isostatic theory of earth deformation. It is rather generally recognized by geologists that the great tangential trusting exhibited in the folding and faulting of so many portions of the lithosphere cannot be explained by simple vertical isostatic movements. Vertical adjustments between small isostatic blocks to the extent of a few miles give horizontal components of force very trivial compared with those required to produce overthrusts of 20 miles and to jam strata into belts of isoclinal folds. The observed folding and thrust faulting cannot be primarily the result of isostatic adjustment, though forces tending toward such adjustment must be in the total equation of forces.

PENEPLANATION

Assuming perfect isostatic adjustment, a mountainous block eroded to the level of the sea projected beneath the mountains[1] will rise theoretically to nine-tenths of its original height according to Bowie,[2] or nine-elevenths of its original height according to Lawson.[3] The net reduction in elevation thus amounts to only two-elevenths on the larger estimate. So planation continues. The column, theoretically, keeps rising with the progress of denudation, and on this basis a tremendous amount of erosion is required to reduce it finally to a condition of stability (baselevel). Bowie has recognized and discussed this.

Let us compare this with the Pennsylvania Appalachians. For the Tyrone-Harrisburg section the eroded folds have been restored in cross section according to what seemed likely projections of curvature. By this method the average height of the restored land surface above the existing Kittatinny peneplain proved to be 3.01 miles, or about 16,000 feet.[4] This block cut down 16,000 feet, should rise

[1] For the complexity of such a case see "The Level of Baselevel," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 166–73.

[2] William Bowie, *U.S. Coast and Geod. Surv. Spec. Pub. 99* (1924), p. 41.

[3] A. C. Lawson, *op. cit.*, Vol. VIII, No. 46 (1924), p. 10.

[4] "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. XVIII (1910), pp. 237–43.

13,000 feet in consequence, assuming perfect isostatic adjustment (see Fig. 2). On this basis, calculation shows that the block would have to be cut down five and a half times its elevation above sea level, or 88,000 feet, to bring it finally to baselevel. Yet in developing the remarkable Kittatinny peneplain it has been cut down only about 16,000 feet! The oldest rocks exposed in the highest anticlines are of Ordovician age; the youngest beds in the deepest synclines are the Pottsville of the Pennsylvanian.

If the mountain block has only nine-tenths of the specific gravity of the heavier rock to come in below to restore the postulated isostatic equilibrium, as assumed by Bowie, peneplanation in harmony with the isostatic theory would necessitate the removal of even greater thicknesses of rock. Baseleveling of the 16,000-foot mountain system on a nine-tenths basis would require the erosion of 160,000 feet of rock. The nine-tenths assumption thus leads to results still less in accord with the geologic observations than the nine-elevenths assumption, though based upon more probable differences in density.

Whatever theory one may entertain, the depth of erosion of the Pennsylvania Appalachians in any case has not been startling. The 16,000-foot average for the whole Tyrone-Harrisburg section probably expresses fairly well the general order of magnitude. Should one, however, object that this estimated height of the mountains is excessive, he should recall that a vast area in Tibet averages today some 15,000 feet above sea level, and the Himalayan mountain chains average considerably higher, Mount Everest attaining the great height of 29,141 feet. The Bolivian Plateau averages 13,000 feet in elevation, and the Andes, flanking it on both sides, run much higher. To baselevel the Bolivian Plateau alone, on a nine-elevenths basis, would require the removal of $13{,}000 \times 5.5$, or 71,500 feet of rock. To baselevel a tract only 5,000 feet high, on a nine-elevenths basis, requires the removal of 27,500 feet of rock. The newly folded Appalachians were hardly so puny a range as that.

This notable discrepancy indicates faulty assumptions somewhere. Some of the discrepancy may possibly be attributable to erosion and consequent isostatic rise during the period of folding, but this seemingly must be only a very partial explanation.

Baseleveling requires that the denudation area remain essentially still-standing for a long period of time. It is, of course, possible that under the conditions of baseleveling, some isostatic compensation is accomplished in some manner not yet recognized. But the phenomenon seems to indicate a strength of earth shell capable of maintaining the denudation area in a state of quiescence while it is undergoing considerable reduction in elevation in the later stages of the erosion cycle.

GEOSYNCLINES

The formation and sinking of geosynclines must be due primarily to some other cause than loading alone. Lawson has shown that a plain on which sediments are deposited can be depressed, by weighting alone, less than two-thirds as much as the thickness of the sediments. A sag of any kind at the surface, due to deposition of sediments, is impossible.[1] Once formed from other causes, accumulation of sediments tends to cause further depression, but so far as the sediments themselves are concerned, the trough fills up much faster than it sags.

Striking foredeeps in the oceans parallel chains of islands and coastal mountain ranges, as off the Aleutian Islands, Japan, the Philippines, Tonga, off the west coast of South America, etc. They are downwarped troughs alongside of upwarped belts. Since they are now topographic depressions below the adjoining floor of the ocean, they are not due to deposition. Like geosynclines they are ready to receive sediment, but sediments have not yet reached them in great volume.

Thus we see that both geosynclines and folded mountain ranges are developed independently of isostasy. Isostasy is clearly not the operating cause. It is a principle always in operation, like erosion of the land, but is not the primary cause; it plays a very secondary rôle. Unless we work on that basis we are flying in the face of the facts and can get nowhere.

The spectacle of a geosyncline sinking and receiving sediments throughout most of the Paleozoic (like the Appalachian trough) and then relatively suddenly reversing itself (at close of Paleozoic) to go up into mountain ranges is a dramatic one. A sinking heavy segment

[1] *Ibid.*, p. 17.

throughout the Paleozoic suddenly becoming light and going up to mountainous heights—isostasy cannot do that. But here we are unfair to isostasy. It is not a force. It should not be expected to throw things out of adjustment. It is merely a tendency to get things into a state of balance or, if in equilibrium, to keep them so. It should not be asked to do more. This has been said before, but too commonly ignored.

MELTING OF ICE SHEETS

Following the melting of the Pleistocene ice sheets, the areas of former thick ice covering have risen with respect to sea level. The rise seems to have been greatest where the ice was thickest. In Fennoscandia, according to Högbom, the maximum rise was 275 meters over the northern Baltic region. This area was the center of ice dispersal. From here the postglacial rise has diminished gradually to zero toward the former ice margin. The uplift is believed to be the consequence of removal of ice load which had previously depressed the rock surface, and the fact that the line of zero uplift is located considerably short of the ice border is taken to mean that the marginal portions of the ice sheet were not thick enough to cause yielding of the underlying lithosphere.

In the Canadian shield the postglacial rise was over 700 feet where the ice had been very thick, and diminished toward the ice borders. Leverett, however, has recently pointed out some lack of correspondence between the area of weighting and that of uplift. "The shorelines show no tilting in the south half of the Lake Michigan basin, nor in all of the Erie basin except the northeast end. Yet the ice sheet extended far beyond the limits of these basins, and must have been thousands of feet thick in parts unaffected by tilting."[1]

The phenomena connected with the loading and unloading of the earth shell by ice sheets seem to constitute the most tangible manifestation of crustal movements on an isostatic basis. The earth shell responds to the burden of the thicker portion of a great ice sheet, but is strong enough to bear the weight of the thinner portions of the sheet without yielding. The yielding has not been of a simple nature, but has taken place in a succession of waves with a

[1] Frank Leverett, "Problems of the Glacialist," *Science*, Vol. LXXI (1930), p. 52.

somewhat complex record.[1] This testifies to considerable strength and stress-accumulation in contrast to continuous liquid flow. Such is not the conventional isostatic conception. In this respect the prevalent isostatic conception needs modification.[2]

A portion of the crustal yielding under an ice load is apparently due to elastic compression, followed by resilience upon removal of the load. Another portion of it is due seemingly to solid rock flow—rock recrystallization by idiomolecular transfer—illustrated by the gradual bending of very old tombstones, or by the movement of glaciers by recrystallization combined with shearing.[3] This is very different from liquid flow, the concept which permeates the whole of isostatic literature. One therefore has the choice of using the recently suggested term, "elastasy," or, if standing by the term "isostasy," of using it in a correct dynamic sense.

WHAT DOES THE GEODETIC EVIDENCE SHOW?

THE NATURE OF COMPENSATION

Deflections of the plumb-line and gravity determinations indicate that the high-standing portions of the lithosphere are, in general, underlaid by rock material of lesser density than the low-standing areas. The theorem of isostasy is that elevation is more or less compensated by rock density. The well-known Pratt and Airy theories of the manner of this compensation, which appeared in 1855, present two definite geometric concepts which may be taken to represent two extremes. The first portrays a floating crust comprising blocks of different density, all reaching down to a common level ("the depth of compensation"); the second postulates a crust of light material of varying thickness floating in heavier material beneath. Both assume a thin solid crust floating on a liquid interior, a very simple but, of course, obsolete conception today.

Hayford and Bowie, building on the Pratt hypothesis, have assumed that compensation is complete and then on this assumption

[1] A. Born, cited by Chester R. Longwell, "Geological Significance of Isostasy and Gravity Measurements," *Geog. Rev.*, Vol. XV (1925), p. 127.

[2] See T. C. Chamberlin, "Intrageology-Elastasy vs. Isostasy," *Jour. Geol.*, Vol. XXXV (1927), pp. 89–94.

[3] Rollin T. Chamberlin, "Instrumental Studies on the Nature of Glacier Motion," *ibid.*, Vol. XXXVI (1928), pp. 21–30.

claim to have found by calculation that the topography of large portions of the earth's surface is very nearly compensated by density. For these calculations a depth of compensation must be selected. Four alternative hypotheses of density distribution and depth of compensation have been put to the test of satisfying the equations. These are: (1) uniform compensation to depths of 76 miles (Hayford) or 60 miles (Bowie); (2) uniformly decreasing compensation to a depth of 109 miles; (3) the "Chamberlin compensation" to a depth of 178 miles; and (4) the compensation all accomplished in a subterranean layer 10 miles thick and averaging 35 miles below the surface. So far as satisfying the equations is concerned, all four types were found to work equally well. To the geologist, who thinks in visual terms rather than in mathematical concepts, these equivocal results seem strange. They suggest that almost any arrangement will satisfy the requirements of this method.

But a more incisive analysis shows that it is really the effective depth of compensation which controls.[1] In each of the four cases the center of gravity of the compensating material was located at about 35 miles below the surface. So long as the gravitational effects are centered here in each case, the effect is about the same in all, and it does not make much difference how the compensation is accomplished. In any case the method is not very discriminating, geologically. As Harmon Lewis has pointed out, instead of complete compensation at a given depth there might equally well be overcompensation at a greater depth, or undercompensation at a lesser depth.[2] The results indicate a general tendency toward compensation and seem to establish the general principle of isostasy, but they tell nothing as to how that compensation is actually effected. One way, apparently, will satisfy the geodetic data about as well as another.

Another disappointing feature is that tests of regional versus local compensation likewise have so commonly yielded equivocal results. This has even led one or two geologists to suspect a mathe-

[1] Joseph Barrell, "The Status of the Theory of Isostasy," *Amer. Jour. Sci.*, Vol. XLVIII (1919), pp. 324–31.

[2] Harmon Lewis, "The Theory of Isostasy," *Jour. Geol.*, Vol. XIX (1911), pp. 603–26.

matical fallacy affecting the whole geodetic method of procedure. In any case, it is clear that the present methods are not discriminative, and that the geodetic evidence does not indicate how the postulated compensation takes place.

YIELDING OF THE LITHOSPHERE

What we know of the rocks of the lithosphere indicates great heterogeneity. Myriads of intrusions of different specific gravity cut the earth shell. Hence the simple picture of blocks, each of uniform density, extending down to a common level some 60 miles below the surface, does not harmonize with geologic knowledge. It is much too simple to fit the actual earth case; it is geometric not geologic.

The yielding of the lithosphere is partly by solid-rock movement under differential stress and partly by liquid flow of magmas. Each is a means of accommodation to stress, but their behavior is different. Let us consider first solid-rock movement. The expression "zone of flow" has proved unfortunate because to so many geologists the word "flow" connotes liquidity which, excepting local masses of magma, is not the condition of the main mass of the earth. I think we must recognize that the "zone of flow" may extend all the way to the surface of the earth, or even above the surface. The tombstone gradually yields to stress by rock flow—slow recrystallization by transfer of molecules from situations of greater stress to positions of less stress. Movement of solid masses by rock flow also takes place in the same way deep below the surface. But for this a sufficiently strong differential stress is required. As F. D. Adams has shown, the increased cubic compression with increasing depth causes a strengthening of the rocks which necessitates in turn greater stress differences to cause deformation.[1] On the other hand, the rise of temperature with increase of depth works in the opposite direction. The case becomes complicated, and cannot be further considered here. For us, it suffices that the outer seven-eighths of the globe are overwhelmingly solid with notable elasticity and rigidity, but yielding under sufficient differential stress. The duration of stress application is a factor in determining the nature and extent of the deformation. For our problem it is particularly important to

[1] F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *ibid.*, Vol. XX (1912), pp. 97–118.

recognize that the earth material, being dominantly solid, the stresses are directed, or oriented, rather than hydrostatic as in a liquid. The axis of least stress (line of least resistance) comes into play, and, by determining the stress difference and its direction, determines the direction and nature of the yielding which takes place. With greatly varying conditions from place to place and time to time, the yielding by solid flow is likely to be heterogeneous in nature and variable in direction.

Wherever there are magmas, hydrostatic mobility is present. Liquid magmas, freer to move if conditions permit, should be an important aid in establishing equilibrium. Hence, in accordance with the geologic concept, a working toward isostatic equilibrium should be accomplished partly by solid flow and partly by liquid flow. These two processes, operating on different principles, should naturally give complex, heterogeneous compensation.

NO SINGLE TYPE OR UNIFORM DEPTH OF COMPENSATION

Is the so-called depth of compensation a physical entity? I doubt it. The geodetic determinations are not discriminative. Bowie's estimate of depth of compensation for the whole United States is 37 miles (60 km.); for the mountainous areas, 60 miles (96 km.), the areas of greater relief according to his belief affording the better basis for determination.[1] Earth processes in general are very complex, and compensatory processes should prove no exception to the rule. Whatever isostatic compensation there may be, we may expect to be accomplished partly by solid-rock movement, which is complex in nature, and partly by transfer of liquid magma. Isostatic equilibrium, thus established, should be by heterogeneous compensation. I believe that compensation takes place in some places and at some times in one way; at other places and at other times in other ways; no uniform depth, or any single type of compensation, seems consistent with the complex, variable factors involved. We are familiar with the simple concept for the use of mathematics, but we need a complex, composite one for the actual earth, whose many variables transcend the powers of mathematics. The principles involved in both the Pratt and Airy hypotheses are likely to enter into this,

[1] William Bowie, *Isostasy* (1927), p. 96.

but each in a more complicated manner than has yet been recognized.

ELEVATION AND ROCK DENSITY

Henry S. Washington has found a general agreement between elevation of the land and rock density.[1] Higher specific gravity characterizes the rocks of the lowlands, and lower specific gravity those of the elevated tracts. These, of course, are surface rocks, but so far as they are igneous they represent magmas from deep below the surface. This general agreement seems to confirm the principle of isostasy. But exceptions also exist, and some of them are striking. Isostasy, though a working principle, can be overworked.

ISOSTASY IN AREAS OF LOW RELIEF

Over large portions of the interior of North America there is little topographic relief to be compensated. For the flattish plains compensation is not very significant, except as the gravity values are consistent with the general elevation. Yet large anomalies occur there. The exceptionally high positive anomaly near Minneapolis is explained by postulating very heavy rock near the surface in that area since abnormal density of rocks near a gravity station exerts a dominating influence on the instrumental results.[2] But this explanation is just as applicable on a non-isostatic hypothesis as on the isostatic theory.

The largest gravity anomaly in the United States is near Seattle, Washington. According to Bowie, this anomaly, assuming no compensation whatever, amounts to −0.111 dyne. On the assumption of uniform compensation to a depth of 113 kilometers (the type preferred by the geodetic survey), the anomaly is −0.093 dyne.[3] Hence introducing the factor of theoretical compensation into the calculations has little effect on the anomaly at Seattle. Isostasy is really indeterminate from data obtained from stations in regions of low relief. It loses much of its importance in flat areas, and such areas

[1] H. S. Washington, "Isostasy and Rock Density," *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), pp. 375–410.

[2] David White, "Gravity Observations from the Standpoint of the Local Geology," *ibid.*, Vol. XXXV (1924), pp. 207–77.

[3] William Bowie, *Isostasy*, (1927), pp. 98–102.

form a much greater part of the earth's surface than do those of high relief. Alternative hypotheses are not excluded.

Can we be certain, then, that peneplains are in a state of isostatic adjustment? Or is this largely an inference from the fact that mountainous tracts seem to show considerable compensation? At all events the real test of the isostatic theory appears to lie in the limited regions of high relief. We turn, therefore, to these portions of the globe to see if we can discover what probably takes place.

HOW THE PROCESSES MAY OPERATE

Young mountains, like the Alps, show a marked deficiency of density and, at the same time, a moderate excess of mass.[1] An analysis of the mountain-building processes shows why this should be so.

1. CRUSTAL SHORTENING AND UPWARD BULGE ALONE

As the thick accumulations of weak and light sediments in a geosyncline are horizontally compressed into a much narrower folded mountain belt, they are telescoped by thrust faulting and squeezed together into rising folds, so that the cover of light sedimentary rocks in the mountain belt becomes still thicker than before folding. Since gravitative attraction varies inversely as the square of the distance, this exceptional amount of light material in the upper portion of the rock column gives a low value to the gravity determinations.[2] On the other hand, crumpling together in the process of crustal shortening has brought additional material into the folded belt. Without assuming any isostatic compensation as such, pendulum observations would therefore reveal an excess of material in the mountains but, owing to the low density in the upper part of the rock column, less excess of mass than would be expected from the elevation of the mountainous tract. The elevation has thus been partly compensated, in effect, by rock density, though on a purely diastrophic basis without the help of isostasy and its postulate of a very weak earth crust. So far so good, but this is only part of the problem.

2. BATHOLITHS

Characteristic of strong mountain folding is the intrusion of batholiths in the heart of the range in a late stage of the deformation.

[1] A. Born, *op. cit.*, p. 75; Chester R. Longwell, *op. cit.*, p. 124.

[2] C. O. Swanson, "Isostasy and Mountain Building," *Jour. Geol.*, Vol. XXXVI (1928), pp. 411–33.

As a rule these are composed of the lighter plutonic rocks. Let us assume that, in many cases, there has been magmatic differentiation, with a concentration of the heavier differentiates into the lower reaches of the magma and of the lighter differentiates in the upper portion. This process of segregation of the lighter constituents toward the surface does not alter the total weight of a deep rock column, provided the transfer of material has been essentially vertical so as to remain in the same column. But the value of g, determined at the surface, becomes less, because the center of gravity of the column has been lowered and the light rocks near the surface have a preponderating effect on the observed gravity values. Therefore, even though there may have been no actual change in the weight of the whole rock column, the geodetic investigations would appear to indicate a reduction of mass because of the change in distribution of density. The greater the vertical rise of the lighter differentiates, or settling of the heavier portions, the more pronounced the apparent effect. An excess of mass piled up in mountain building as a burden supported by the strength of the earth shell would thus appear less, because of magmatic differentiation in batholiths, than would actually be the case. This carries us one step farther in explaining geodetic observations in the light of geologic processes.

3. TRUE ISOSTATIC COMPENSATION

In addition to the upward bulge of a mountain range in consequence of folding, we may accept also some downward yielding within the deformed zone. As the upper portion of the folded strata moves upward in the line of least resistance, the deeper portion is forced downward. A diagram is admittedly dangerous, for it may appear to commit the author to a single definite concept without sufficient allowance for possible alternatives. Yet, if a diagram cannot be drawn, the concept is too vague to be of much value. Figures 3 and 4, therefore, are an attempt to sketch the supposed movement of material in the process of mountain folding, according to the wedge theory.[1]

The ultimate cause of this diastrophism is taken to be a rearrangement of material in the interior of the earth in favor of greater den-

[1] Rollin T. Chamberlin, "The Wedge Theory of Diastrophism," *ibid.*, Vol. XXXIII (1925), pp. 755–92.

sity under the influence of gravity,[1] whereby the surficial portion of the lithosphere becomes too large circumferentially for the portion beneath, and tangential thrusting develops. In yielding to this

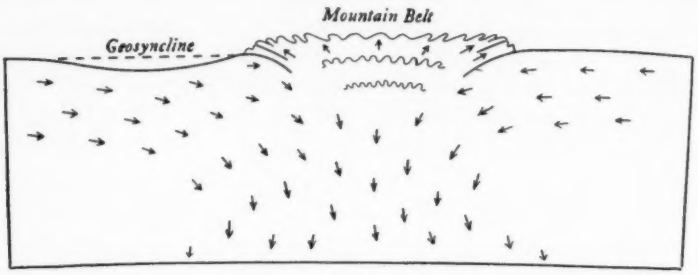

FIG. 3.—Postulated movement of material by solid rock flow and local shearing in the process of mountain folding. The mountain belt is folded and faulted upward and an adjoining tract depressed as a geosyncline. Rearrangement of material in the main mass of the earth in favor of greater density is here taken as the activating cause. A two-sided symmetrical range is the type portrayed in this diagram.

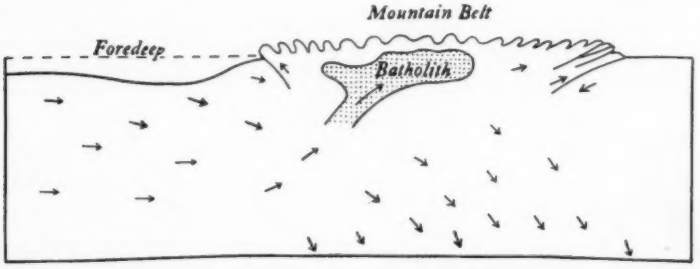

FIG. 4.—A two-sided asymmetrical mountain belt with foredeep and batholithic intrusion. A liquid phase (movement of magma) is here included.

thrusting the squeezing-up of mountain folds and the rise of fault slices impose an added burden upon the supporting lithosphere beneath. On the isostatic principle, the added weight means an increased gravitative force directed downward and outward beneath the excess mountain burden. This serves to limit the extent of the

[1] T. C. Chamberlin, "Certain Phases of Megatectonic Geology," *ibid.*, Vol. XXXIV (1926), pp. 1–28.

crustal burden developed by the horizontal compression. These opposing forces in the outer shell work in conjunction with the postulated compacting and rearrangement of the deeper interior.

We therefore picture the lower portion of the deformed wedge-mass as forced downward, while the upper part, forced upward in the line of least resistance, protrudes as mountains. Since the development of a major mountain system seems to involve far reaching readjustments within the mass of the earth, the roots of the downward-converging wedge-block do not represent the lower limits of the whole deformative movement. Accommodation to the general earth stresses must be much more pervasive. Hence no division of the lithosphere into a crustal and a subcrustal portion enters into this concept. We are considering all to be solid lithosphere, except for local occurrences of magmas and the central core, as yet of undetermined nature.

It is possible that the inauguration of an orogenic movement is to be sought in more than average mobility of material beneath a geosynclinal tract whereby interior readjustment is there localized and concentrated, and the more superficial shell is then crowded together above in folds in response to the tangential stresses consequently developed. That is a possible lead for further study. In this the reader may, perhaps, infer the influence of the *Verschluckungstheorie* advocated by Ampferer[1] and Schwinner,[2] but their convection hypothesis is based on conceptions of fluidity. The present paper is based upon an earth dominantly solid. The two work differently.

The geanticlinal-geosynclinal couple[3] is a widely prevalent phenomenon. If the adjustment to a shrinking interior draws down material from a belt somewhat broader than that which is folded, a foredeep, or geosyncline, paralleling the mountain range may be formed (see Figs. 3 and 4). Particularly would this be true if some of the igneous material appearing in the folded belt, either as intru-

[1] Otto Ampferer und Wilhelm Hammer, "Geologischer Querschnitt durch die Ostalpen," *Jahrb. geol. Reichsanstalt, Wien.*, Vol. LXI (1911), pp. 531–710.

[2] Robert Schwinner, "Vulcanismus und Gebirgsbildung," *Zeitschr. für Vulcanologie*, Vol. V (1919).

[3] Rollin T. Chamberlin, "The Significance of the Framework of the Continents," *Jour. Geol.*, Vol. XXXII (1924), pp. 568–69.

sions or in volcanoes and surface flows, came up diagonally[1] from beneath the adjoining trough, as Willis has suggested.[2]

As noted above, the rock material in the lower portions of the strongly deformed mass becomes more deeply depressed beneath the surface and, to some extent, it may also spread outward beneath the immediately adjoining tracts. At the same time that the denser, deep-seated rocks are depressed and in part move outward below, lighter superficial rocks are crowded into the mountain column above in the crustal shortening process. The result is that the protruding mountain mass becomes a lesser burden to be supported than would otherwise be the case. Some isostatic compensation has taken place.

4. CONTEMPORANEOUS EROSION

During an orogenic revolution erosion is actively at work steadily reducing the excess mass in the rising mountain chains. In this way, also, we see a working toward equilibrium.

SUMMARY OF ISOSTASY AND MOUNTAIN BUILDING

Four different processes connected with mountain building thus may operate to give the reduced gravity values found in recently folded ranges. But all of these processes combined, for a considerable time at least, fail to prevent the development of some excess mass in the mountainous belt. The excess mass is supported by the strength of the earth. If this analysis of the operating geologic processes be correct, we see how geosynclinal strata may be folded and faulted into mountain ranges, exhibiting the observed geologic phenomena, and yet at the same time having the possibility of satisfying the geodetic determinations. We see a partial harmonization of geologic facts and geodetic data, so far as deformed mountain ranges are concerned.

THE RÔLE OF ISOSTASY

The principle of isostasy has come to stay, but it appears to have been overworked. If folded mountain chains were formed by the

[1] R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *ibid.*, Vol. XXXV (1928), pp. 331–49.

[2] Bailey Willis, "Continental Genesis," *Bull. Geol. Soc. Amer.*, Vol. XL (1929), pp. 281–336. And "Metamorphic Orogeny," *ibid.*, pp. 557–88.

forces tending toward isostatic equilibrium, departures from adjustment should be greatest immediately before the mountains were built. Making the mountains should restore equilibrium, and the adjustment should be most nearly achieved, and most perfect, just as the forces had been spent in completing the mountain folding. Just the reverse, however, appears to be the case. Recently folded mountains are particularly out of adjustment. Hence, because of this and other considerations already discussed, we are forced to conclude that mountain folding is primarily independent of isostasy and in direct opposition to it. The mountains are formed in spite of isostasy. Isostatic forces, however, are all in the whole equation of mountain-building forces, and play their appropriate part, but that part is secondary and subordinate. Their function is to preserve balance or to restore balance disturbed by other forces and processes. Isostasy is not an accelerator; rather is it a restrainer. Isostasy works in opposition to mountain folding; it works in opposition to erosion. When things are doing, or done, it tends to restore equilibrium. Limited thus to its proper sphere, it is an important principle and should be used as such.

THE APPALACHIAN STRUCTURAL FRONT[1]

PAUL H. PRICE[2]
Cornell University

ABSTRACT

The Appalachian structural front marks a comparatively narrow zone, east of which the rocks have been greatly mashed, folded, and faulted, while west of this zone the rocks lie more nearly horizontal. This is shown by cross-sections. The structural break closely parallels the axis of the trough of deposition from at least early Silurian to the close of Pottsville time and therefore follows an inherited line of weakness. The type of failure was governed by the shape of the basin and the character of the beds, whether competent or incompetent, and their position in the stratigraphic section.

INTRODUCTION

A glance at a geological map of Eastern United States immediately suggests to a student of geology that there is a marked difference between what is commonly known as the Appalachian Plateau and the area lying immediately to the east known as the Appalachian Valley or Valley and Ridge physiographic province. Examination of detailed structure sections will further emphasize that there is a structural break at or near what is commonly called the Cumberland escarpment, Allegheny front, and Catskill escarpment. This paper is written in an attempt to explain the position of this structural feature.

DEFINITION OF THE APPALACHIAN STRUCTURAL FRONT

The Appalachian structural front should be distinguished from the erosional front. It is here designated as the most westerly major fold or fault of the Appalachians and lies in what is now called the Valley and Ridge physiographic province; while the erosional front is marked by the Catskill, Allegheny, and Cumberland escarpments, and varies in height from 500 to 1500 feet above the adjacent valley. In general, although there are exceptions, the surface rocks west of

[1] This study was made possible by the Eleanor Tatum Long Graduate Scholarship in Structural Geology. The writer wishes to express his appreciation to Professor C. M. Nevin, under whose direction the study was carried on, for his helpful suggestions and kindly criticism.

[2] Present address, West Virginia Geological Survey and West Virginia University.

the front are of Carboniferous age, while east of the front they are older, including especially those from Devonian to Cambrian. The distance between the structural front and the erosional front varies from 0 to 5 miles. Inasmuch as this feature is continuous from Alabama on the southwest to the east coast of Labrador on the northeast, a distance of approximately 1,500 miles, one term should be used to designate it throughout. It is therefore proposed to call that zone marking the division between the gently folded plateau structure on the west and the strongly folded belt on the east the "Appalachian structural front." Unless otherwise specified the terms "front" and "Appalachian front" are hereafter used in this sense.

For lack of detailed information, discussion will be limited to that portion of the Appalachians south of the New York state line, although it may be inferred that the general conclusions and suggestions based on this portion of the system will apply throughout the entire length of the front.

DETAILED STRUCTURE ALONG THE APPALACHIAN FRONT

Viewing the Appalachian front in its entirety, the outstanding structural feature is the difference in failure of the rocks east and west of this zone. To better emphasize this point a series of cross-sections along the front from central Pennsylvania to central Alabama have been prepared. These bring out this relation much better than a written description (see Fig. 1, 2, 3, 4).

Beginning in central Pennsylvania it is seen that in passing from east to west (Fig. 1), the strata are intensely folded with some faulting up to and including the Nittany Arch, the beds of which reach the vertical in Bald Eagle Mountain; but immediately west of these strong anticlines the rocks soon attain a nearly horizontal attitude and continue so for many miles. In southwest Pennsylvania and in northern West Virginia several folds of magnitude, including the Chestnut Ridge anticline, lie some 40 miles west of the front, and approximately parallel it.

Across Maryland and northern West Virginia (Fig. 2) conditions are somewhat similar to those of Pennsylvania. In central Pennsylvania the Nittany Arch, the western limb of which forms Bald

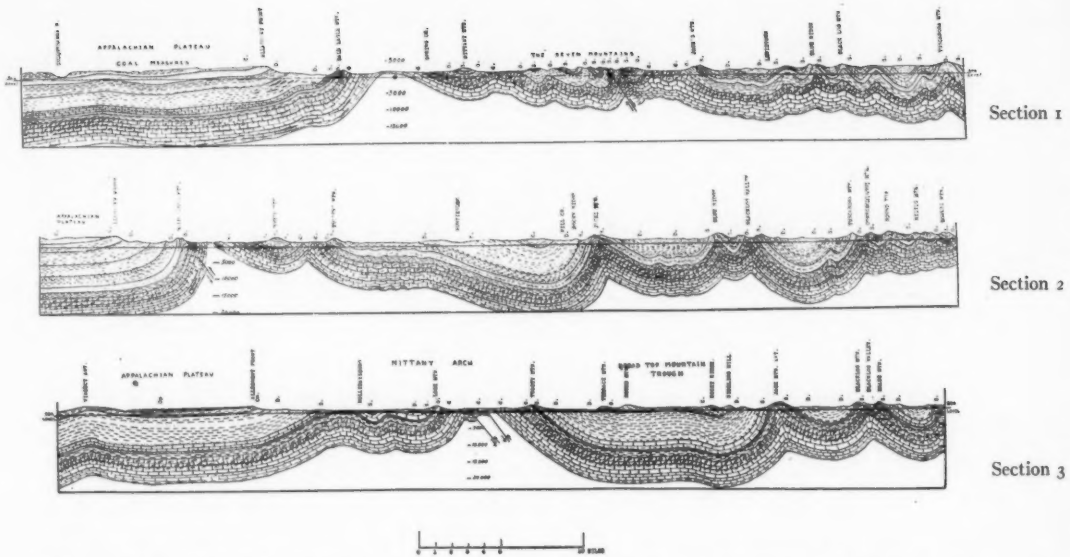

FIG. 1.—Cross-sections in Pennsylvania (Secs. 1, 2, 3). Sec. 1. A portion of geological sections of Pennsylvania by Henry D. Rogers, with interpretations by the writer. This section extends from near the Susquehanna River eastward across the Allegheny and Appalachian fronts, through Lewistown to Tuscarora Mountain. Sec. 2. Same source, with interpretations by the writer. This section begins west of the Allegheny front and continues eastward through Tyrone and Huntingdon to Bowers Mountain. Sec. 3. This section begins on the Appalachian plateau and passes eastward through Hollidaysburg to near Tuscarora Mountain. The middle 35 miles of this section, extending from the Willmore syncline, west of the front, to Jacks Mountain anticline on the east, was kindly furnished by Charles Butts.

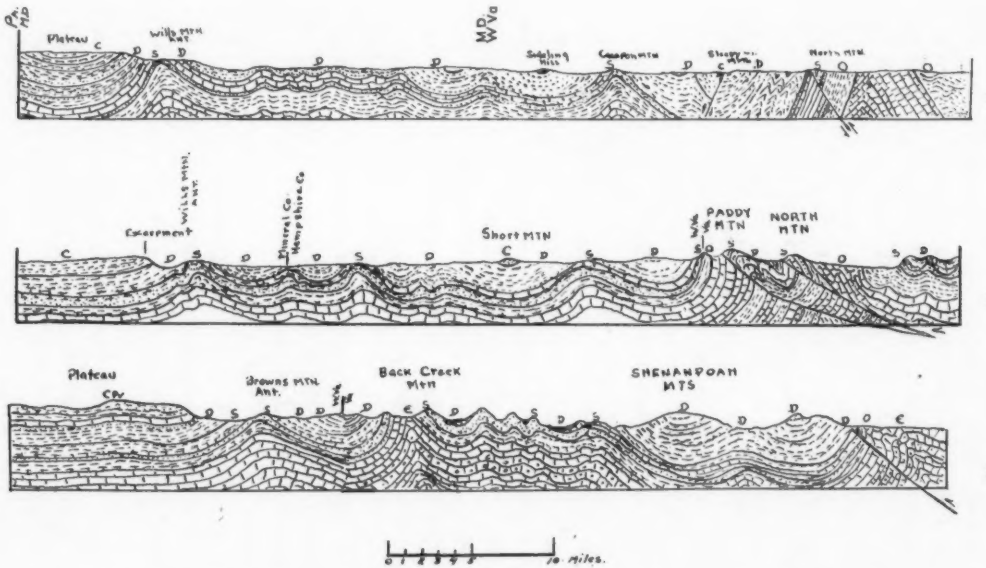

FIG. 2.—Cross-sections in Maryland–West Virginia–Virginia (Secs. 4, 5, 6). Compiled from Maryland, West Virginia, and Virginia Geological Survey publications. Sec. 4. Beginning on the plateau west of the front the line of section continues eastward across Wills Mountain anticline in Maryland into West Virginia, crossing Sideling Hill, Cacapon, and North Mountains. Sec. 5. This section begins in Mineral County, West Virginia, west of the front and extends southeast across Wills Mountain anticline; across Hampshire County into Virginia on Paddy Mountain. Sec. 6. Beginning on the plateau in east central West Virginia this section continues southeast across Browns Mountain anticline into Virginia.

Eagle Mountain, represents the most westerly major fold from Williamsport to Hollidaysburg, Pennsylvania. At this latter point the structure offsets or interfingers with another major structure that develops into the Wills Mountain anticline; and this in turn comprises the most westerly major fold across Maryland into West Virginia, continuing to the southern end of Pendleton County, where the front is again offset, but in this case to the west, by the Browns Mountain anticline. These major folds which represent the structural front, and might be spoken of as the Nittany and Wills Mountain arches, are typical of Appalachian structure. They are long, unsymmetrical and comparatively straight, and give a prominent relief to the area. The west limb is the steeper and often stands vertically, or slightly overturned, for a distance of many miles. Throughout this distance of over 200 miles the formation which gives the topographic relief is the Medina sandstones, while the erosional escarpment, marked by the Allegheny front a few miles to the west (2–4 miles), is capped by the nearly horizontal Coal Measures.

In east central West Virginia, which incidentally lies about midway between the two larger depositional basins; namely, Pennsylvania and Alabama-Tennessee, the front is offset to the west by the Browns Mountain anticline (see Fig. 8); this occurs west of the Allegheny Mountains, the eastern border of which is generally recognized as the erosional or Allegheny Front. Because of its magnitude, however, and its proximity to what may clearly be recognized as the front on both north and south, it is here considered as marking the structural front. The Browns Mountain anticline, in reality an anticlinorium, has been described in some detail by the writer in a report on Pocahontas County, West Virginia,[1] as well as by Darton.[2] This anticline is approximately 55 miles long with an average width of 3 miles, and strikes in an exceptionally straight line 30° east of north. The Medina sandstones continue to give relief to the folds at the front.

In southeastern West Virginia, particularly in Greenbrier, Summers, and western Monroe counties, it is again noticeable that the zone of open folding is carried west of the Front. Attention should

[1] Paul H. Price, "Pocahontas County," *W. Va. Geol. Surv.* (1929), pp. 80–81.

[2] N. H. Darton, "Monterey Folio," *No. 61, U. S. Geol. Surv.* (1898), p. 6.

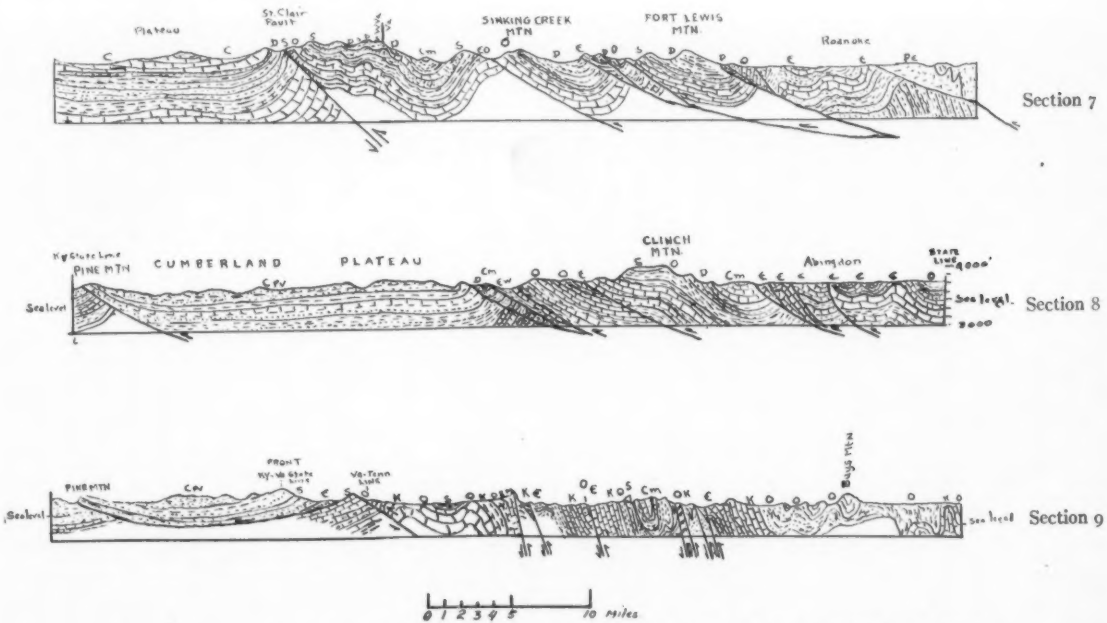

FIG. 3.—Cross-sections in Virginia–West Virginia–Kentucky–Tennessee (Sec. 7, 8, 9). Compiled from various publications of these states. Sec. 7. Begins on the plateau in southern West Virginia and continues southeast across the St. Clair fault into Virginia. In the latter state it crosses Sinking Creek and Fort Lewis Mountains to a few miles east of Roanoke. Sec. 8. This section begins at the Kentucky-Virginia line just west of Pine Mountain and continues southeast across Virginia, passing through Abingdon to the Tennessee state line. Sec. 9. Begins just west of Pine Mountain and passes southeast across the Cumberland fault block into Tennessee to just east of Bays Mountain.

be called to the fact that in this locality the Mississippian strata have attained their greatest development in the entire Appalachian area and that the Greenbrier limestone is a comparatively competent member of the series (see Fig. 7).

From southern West Virginia to central Alabama the striking feature along the front is the prevalence of faulting rather than folding (see Figs. 3, 4, 5). Beginning in southern West Virginia the front is marked by the St. Clair fault. Campbell[1] has stated that this fault is "far-reaching toward the southwest" and he appears to have mapped it across southwest Virginia almost to the Tennessee line; but the name is not carried on the maps, and the descriptions are meager, and there are so many divergent branches in the general system of faults that its exact alignment can scarcely be followed. Reger,[2] however, has traced it from Allegheny County, Virginia, southwest across Monroe County, West Virginia, passing through the Narrows of Virginia into Mercer County, West Virginia, to Cedar Bluff, Tazewell County, Virginia. One very good exposure is to be seen along the highway near the Narrows, Virginia, where New River has cut a picturesque gorge through the mountains. At this locality the writer observed a strike of north 60° east with a dip of 25° to the southeast, which approximately parallels the present attitude of the strata. The exact displacement is not definitely known, but is comparatively large, as the Beekmantown limestone of Lower Ordovician age is now resting against overturned Marcellus shale of Middle Devonian age.

The Cumberland Mountain area will be described under structures west of the Front.

In nearly all cases the faults along the southern end of the Appalachians are thrusts dipping to the southeast with varying amounts of throw; and in most cases the Cambro-Ordovician limestones now rest against Carboniferous strata.

In central Alabama considerable faulting has occurred, but there are comparatively large areas that have not been extensively faulted, as for instance the Cahaba and Coosa coal basins. It will be further noted that the Pottsville sediments have accumulated to great

[1] M. R. Campbell, "Pocahontas Folio," *No. 26, U. S. Geol. Surv.* (1896).

[2] David B. Reger, "Mercer-Monroe-Summers Counties," *W. Va. Geol. Surv.* (1926).

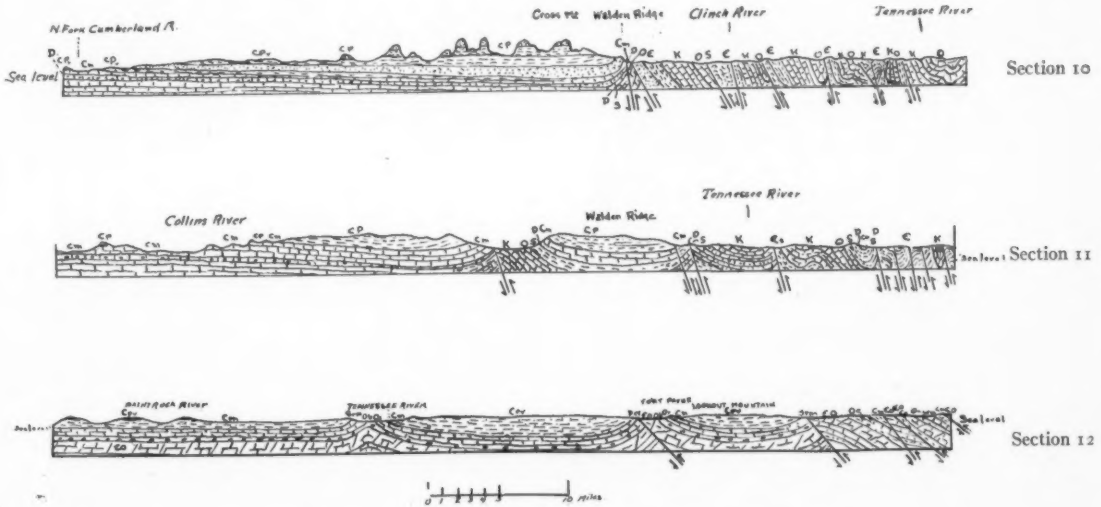

FIG. 4.—Cross-sections in Tennessee (10, 11), Alabama (12). Taken from geological map of Tennessee, 1923; Alabama, 1926. Sec. 10. This section begins well back on the plateau (Cumberland) and trends southeast across Waldens Ridge to near the Tennessee River. Sec. 11. This section roughly parallels number 10 but 80 miles farther southwest. Sec. 12. Begins in northeast Alabama west of Paint Rock River and passes southeast across the Sequatchie (Valley) anticline, Fort Payne, and Lookout Mountains.

thicknesses in these particular areas, thereby localizing the load on the underlying Cambro-Ordovician. Where failure has occurred west of the front, in general the type of deformation is faulting rather than folding. This would seem to show that the controlling factors during deformation were different in central Alabama and southern West Virginia from what they were from the latter area to central Pennsylvania. The reason for this difference will be discussed later.

Finally, attention is again called to the fact that throughout the entire Appalachians folding to the west of the front is more nearly symmetrical than to the east.

STRUCTURE WEST OF THE FRONT

That area lying between the Appalachian front and the Cincinnati arch, together with its southern representative, the Nashville dome, forms a large structural basin, within which are numerous anticlines and synclines and some faults. In the literature this basin is often referred to as the Appalachian geosyncline; but in the present paper it is considered better to limit the use of this term to the former depositional basins.

This structural basin extends from southwestern New York across western Pennsylvania and on into West Virginia. The axis continues southwest across West Virginia to the west central part where its continuity is broken by the Burning Springs anticline which strikes nearly north and south. Southeast of the latter area it continues as the Parkersburg syncline to a point a few miles south of Huntington where it enters Kentucky. In this state the basin as a whole is narrowed by the proximity of the Cincinnati arch and even more so in Tennessee where the Nashville dome has caused the deeper portion of the present structural basin to approach closely the eastern margin of the plateau.

Within this basin the most prominent continuous feature is the Chestnut Ridge anticline. This begins on the Appalachian Plateau in central Pennsylvania, about 30 miles west of Altoona, and continues in a southerly direction, roughly paralleling the strike of the Appalachian system. It leaves Pennsylvania to enter West Virginia at the common corner of Fayette-Preston-Monongalia counties

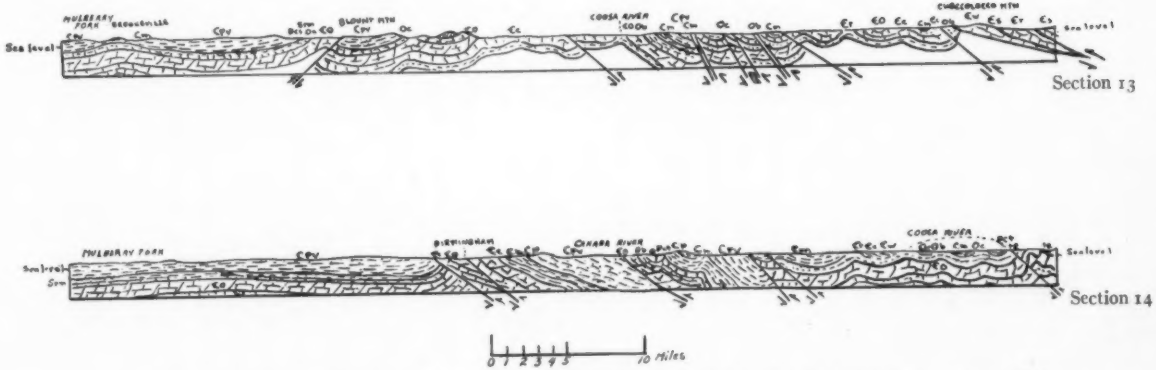

FIG. 5.—Cross-sections in Alabama (Secs. 13, 14). Taken from the geological map of Alabama, 1926. Sec. 13. This section begins near Mulberry Fork, immediately west of the southern end of the Sequatchie (Valley) anticline and continues southeast to Choccolocco Mountain. Sec. 14. This section generally parallels number 13 and lies approximately 50 miles to the southwest.

about 10 miles northeast of Morgantown. From here it continues southwest in a somewhat meandering line across West Virginia with local swells and flattenings, and passes a few miles southwest of Charleston to enter Kentucky at Warfield. From this point the strike of the fold deviates to the west and continues across southern Illinois into Missouri. In the central and western portion of Kentucky, as well as in Illinois, faulting is a predominant feature, although here and there this anticline is fairly regular.[1]

It is not considered necessary to go into much detail regarding this structure, although it should be stated that in Pennsylvania, West Virginia, and eastern Kentucky it is present generally as a low anticline with dips varying from 25 to 100 feet per mile, whereas in western Kentucky and southern Illinois it is marked by a fault zone with westward displacement attaining a thousand feet. Apparently the Chestnut Ridge anticline, a more or less continuous structural feature for over 500 miles, is the reflection of a line of weakness in the basement complex.

In the southern portion of the Appalachians the type of deformation has been such that the front is not clearly delineated. The Sequatchie (Valley) anticline is, however, here considered as lying west of the front and on the Plateau. This anticline is now marked by a long, straight and comparatively narrow valley that begins at Big Lick, in east central Tennessee, and continues southwest into Alabama, with a trend of south 35° west, passing through Guntersville to die out near Blount Springs. The width varies from five to ten miles but the length is approximately 150 miles. The western side of this fold is marked throughout the greater part of its length by a fault dipping to the southeast. The rocks on the surrounding plateau are of Pottsville age, while in the valley the Cambro-Ordovician limestone (Knox) is exposed at the surface.

The Burning Springs anticline in western West Virginia is somewhat exceptional in that it strikes nearly north and south, or transverse to the prevailing trend of the folds. This anticline is a sharp fold that rises very abruptly from comparatively horizontal rocks.

[1] James B. Gardner, "A Stratigraphic Disturbance Through the Ohio Valley, Running from the Appalachian Plateau in Pennsylvania to the Ozark Mountains in Missouri," *Bull. Geol. Surv. Amer.*, Vol. XXVI (1915), pp. 477–83.

It has a length of about 30 miles, a width of less than 5 miles, and a distinct double crest; it has long been notable for the producton of oil and some gas. It is this anticline which breaks the general continuity of the Appalachian structural basin.

In the Cumberland Mountain area of Virginia-Kentucky-Tennessee a fault block of great magnitude occurs. This area has been described in some detail by Wentworth.[1]

INFLUENCE OF STRATIGRAPHY ON THE TYPE OF FAILURE

It has long been a matter of observation that rocks vary greatly in the manner of their yielding to pressure. The detailed experiments of Willis,[2] in which he attempted to duplicate Appalachian conditions, marked a real advance in deciphering the mechanics of this system. It was in this paper that he developed the terms "competent" and "incompetent" folding. Competent folding requires that a rising arch shall lift the load of the overlying formations, or a sinking syncline shall displace the underlying material. Competent folding is characterized by horizontal compression and vertical extension. The folds are broad and mostly open and may be measured in miles. Incompetent folding presents a direct contrast, and the formations involved are inherently too weak in themselves, to either lift the overlying load or displace the underlying material. The mass as a whole is subjected to vertical or radial compression and to horizontal or tangential tension. Typically incompetent folds are small.

An examination of the general columnar sections, Figure 7, will show at a glance the relative amounts of competent and incompetent formations found at or near the Appalachian front from Lock Haven, Pennsylvania, to Birmingham, Alabama. It will further show how heterogeneous is the section vertically and how varied are the deposits horizontally. All types of limestone, sandstone, and shale, with gradations from one into another are present, and thus we find a complex series of extremely varied competency.

The average thickness of sediments along the deeper portions of

[1] Chester K. Wentworth, "Russell Fork Fault of Southeast Virginia," *Jour. Geol.*, Vol. XXIX (1921), p. 353.

[2] Bailey Willis, "The Mechanics of Appalachian Structure," *U.S. Geol. Surv. 13th Annual Report of the Director*, 1891–92.

the Appalachian geosyncline is approximately 30,000 feet. The sediments thin both east and west from the axis of the trough of deposition, but the thinning is more rapid toward the east. In considering the Appalachians in their entirety it is quite important to get the relation of the total vertical thickness of sediments to their horizontal extent, or at least their width from east to west. Assuming an approximate width of 300 miles for the geosyncline, it is readily seen that the ratio of depth to width is roughly 1 to 50. This fact should be kept in mind in any discussion of the deformation at the end of Permian time (see Fig. 6).

The columnar sections, Figure 7, are drawn to illustrate the character and position of the various horizons at the close of Pottsville

FIG. 6.—Diagrammatic section showing the proportionate size of the Appalachian geosyncline to a sector of the earth.

time. A better plan would have been to use the end of Permian time, or just before the major folding, but sufficiently accurate data for the intervening formations were not available. Hence the close of Pottsville time was chosen as a base from which to plot the position of the underlying formations. It should also be pointed out that during the remainder of Pennsylvanian and Permian time the trough of deposition was shifted farther to the west and received sediments only in its northern extension; so that the amount of these sediments present along the Appalachian front is relatively unimportant.

It is unfortunate that the complete Paleozoic section is not seen at any one locality, and composite sections compiled from areas a considerable distance apart, are therefore necessary. In fact it is only in the eastern panhandle of West Virginia that pre-Cambrian rocks reach the surface in the vicinity of the Appalachian front.

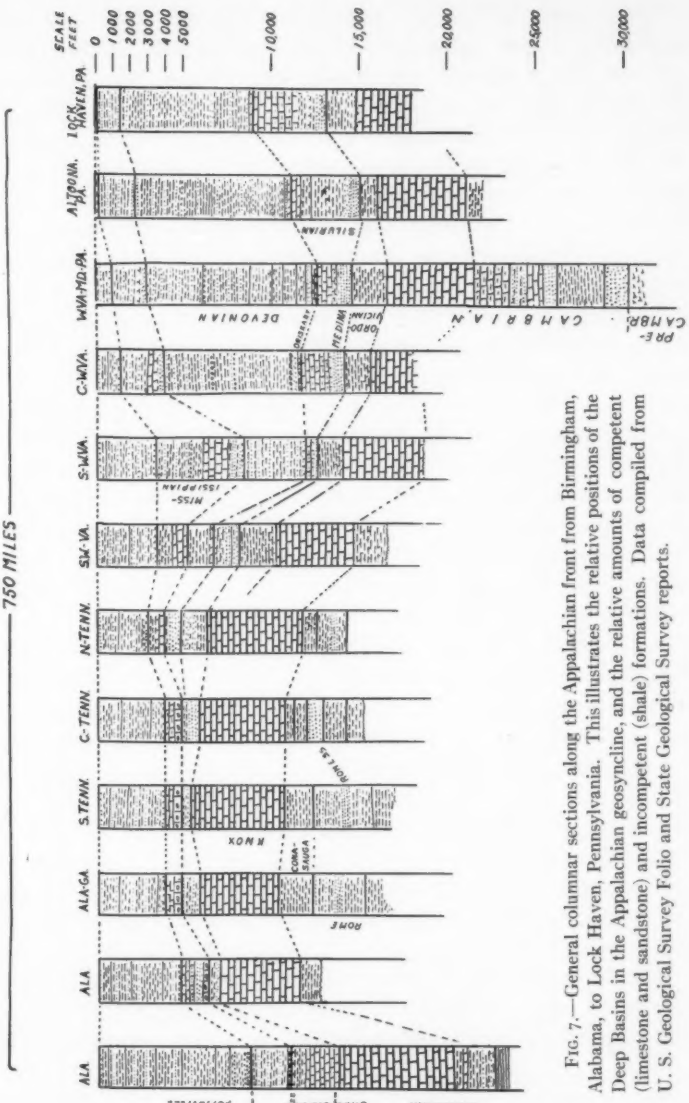

FIG. 7.—General columnar sections along the Appalachian front from Birmingham, Alabama, to Lock Haven, Pennsylvania. This illustrates the relative positions of the Deep Basins in the Appalachian geosyncline, and the relative amounts of competent (limestone and sandstone) and incompetent (shale) formations. Data compiled from U. S. Geological Survey Folio and State Geological Survey reports.

Viewing the Appalachian geosyncline as a whole there are two major depositional basins and a third minor one, namely, the Pennsylvania-Maryland–northern West Virginia basin, the Alabama-Tennessee basin, and a smaller one in southern West Virginia. The Cambro-Ordovician limestone is the competent horizon throughout and it exerted an important influence on the failure of the overlying formations. The relatively competent Silurian sandstones played a secondary rôle in Pennsylvania, Maryland, and northern West Virginia, as did similarly the Mississippian limestone in southern West Virginia.

In the northern district the competent Cambro-Ordovician limestones occur near the base of the section and are overlain by several thousand feet of weaker sediments. These overlying sediments decrease in thickness away from the trough. Furthermore, near the center of this district the Silurian beds are relatively competent, while the succeeding Devonian sediments have a somewhat uniform distribution of competency because of the alternation of shale and sandstone. The same is true of the overlying Mississippian and Pottsville formations. The type of deformation in the northern district is primarily competent folding.

In the southern district conditions are generally reversed. The absence of the upper Silurian and nearly all the Devonian allows the competent limestone to come nearer the surface. In addition a considerable thickness of comparatively weak Lower Cambrian sediments was deposited at the base of the section and the competent Cambro-Ordovician limestones are thus underlain and overlain by incompetent beds. The dominant type of deformation is faulting. One exception to this generalization is the Cahaba coal field of Alabama, where a great thickness of Pottsville beds overlies the competent limestone. The effect of this localized load is reflected in the structure of this basin and faulting is far less noticeable than in the adjoining areas where the overburden was normal.

Keith[1] has recently illustrated the effect of stratigraphy in controlling the type of deformation and reiterated the generalization that where the strength lies at or near the bottom and is overlain

[1] Arthur Keith, "Structural Symmetry of North America," *Bull. 39, Geol. Surv. Amer.* (1928), pp. 335–57.

by a thick series of incompetent beds, the type of failure has been folding; that where the strength occurs near the middle of the section, or between incompetent beds, the type of failure has been faulting, and he has used the Appalachians as an example to prove the relation. This general principle is here granted with one qualification, namely, that in order to get competent folding in the upper portion of a section where the greatest strength lies at the base and is overlain by thousands of feet of sediments, these overlying sediments must, as a whole, also be relatively competent. A majority of the folds northward from central West Virginia are of the open competent type and, as already pointed out, the stratigraphy shows relative competency above the Cambro-Ordovician. If this were not the case, then competent folding in the Cambro-Ordovician would be replaced upward by incompetent failures.

THE STRUCTURAL FRONT IN RELATION TO DEPOSITIONAL BASINS

When the present problem was undertaken it was believed that if the position of the axis and the shape and size of the Appalachian geosyncline could be plotted against the relative amounts of competent and incompetent strata, and their position in the sections, so as to visualize conditions before the Permian deformation occurred, some worth-while conclusions regarding the origin and position of the Appalachian structural front would result. As the study proceeded it soon became evident that it was impractical to get reliable data for complete sections throughout the entire area. It was then decided to restrict the problem to the area south of the New York state line, and to include on the structural map only those formations for which reliable thicknesses could be secured. As a result, it was necessary to limit the contouring to the base of the Silurian at the close of Pottsville deposition. This would not necessarily indicate the complete history of the respective basins but it would give the shape and position of the combined basins at the close of Pottsville. The reason for taking the Pottsville as a reference horizon has already been noted, i.e., the partial absence of younger formations along the Appalachian front.

On the accompanying map (Fig. 8) the combined thickness of Silu-

rian, Devonian, Mississippian, and Pottsville sediments is shown by 1,000-foot contours. Assuming that the topmost bed of this series is

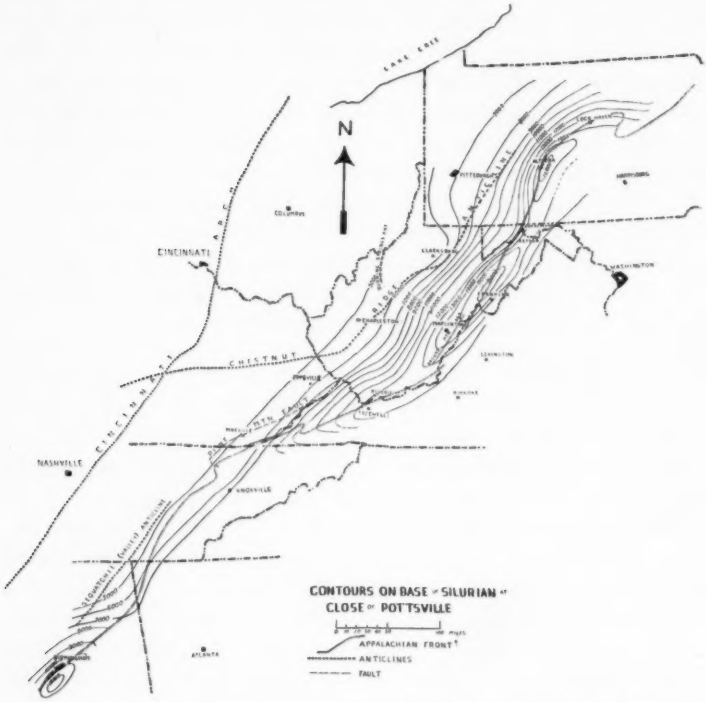

FIG. 8.—Map showing contours on base of Silurian at close of Pottsville time. On this map the thickness of the Silurian, Devonian, Mississippian, and Pottsville sediments is shown by 1,000-foot contours. Assuming the topmost bed of the series is horizontal, the contouring, verging downward, shows in generalized form not only the thickness of the beds at various points but also the general shape of the basin at the close of Pottsville.

horizontal, the contouring, verging downward, shows in generalized form not only the thickness of beds at various points, but the shape of the floor of the basin at the close of Pottsville time.

Beginning in northeast Pennsylvania it is seen that the structural front forms a sweeping curve or offset northeast of Lock Haven. It

is suggested that this follows a line of weakness, inherited from an earlier time, and that the Permian deforming stress was partially expended in folding the localized Pottsville Basin to the southeast. From Lock Haven, the front passes southwest through Altoona, Pennsylvania, Cumberland, Maryland, Keyser, West Virginia, and strikes the Virginia line at the southwest corner of Pendleton County, West Virginia. In east central West Virginia the Browns Mountain anticline, a prominent and continuous feature for some 55 miles, offsets the front to the west some 10 miles. Continuing to the southwest, the front passes through Bluefield, West Virginia, and on to the southwest corner of Virginia, where another small offset is encountered. In Tennessee it continues in a straight line until it encounters the Jacksboro fault, a transverse extension of the southwest end of Pine Mountain fault. Here the front follows the fault for a few miles and then turns southwest across Tennessee, cutting the extreme northwest corner of Georgia, and into Alabama, passing through Birmingham to be concealed beneath the Cretaceous sediments.

The western curvature of the front in central Pennsylvania and again in Tennessee corresponds to what Keith has termed salients.

Let us next consider the trough of deposition. Disregarding the Pottsville basin in eastern Pennsylvania, we find that the trough attains a great depth in central Pennsylvania with a gradual decrease northeast toward Lock Haven. From Altoona the axis of the geosyncline trends nearly due south with a fairly uniform level to Keyser, West Virginia. From here the axis swings more to the west with a slight pitch, and reaches a depth in Pendleton County, West Virginia, equaling that of Altoona, Pennsylvania. From here the axis of the basin swings in a graceful southwest curve, passing through Marlinton, West Virginia, Tazewell, Virginia, to the southwest corner of the latter state and with a progressive decrease in depth. This decrease is a reflection of rapidly thinning Devonian sediments. Incidentally the minor basin in southern West Virginia, developed in Mississippian time, is not brought out by the 1,000-foot contours. In Tennessee the sediments show an increase in thickness to the east, and the axis cannot be definitely located. In Alabama the deep portion of the trough is just south of Birmingham in the

Cahaba coal basin, and is a reflection of the enormous thickness of Pottsville sediments.

In contrasting the position of the Appalachian structural front with the axis of the depositional basin, as represented by sediments from Silurian to Pottsville, their general parallelism is readily seen and is very striking. In fact, Dr. David White has already stated that the early axial Pottsville basin lies near the eastern border of the present Appalachian coal region.[1] This in turn closely parallels the present Appalachian structural front.

PROBABLE SIGNIFICANCE OF THE STRUCTURAL FRONT

It is generally accepted that a mass of heterogeneous sediments will not transmit a tangential stress for any considerable distance. In addition, Willis[2] has suggested that no effective stress can be transmitted through an actively developing fold, which thus does away with the necessity of assuming that folds must be buttressed on one side by an immovable mass. If we accept these generalizations it is evident that we must look to the basement complex for the transmission of stress in sedimentary areas which have been deformed into a series of parallel folds.

In the Appalachian area, however, the position in the section and the physical character of the thick Cambro-Ordovician limestones and dolomites, suggest the possibility that a considerable portion of the deforming stress may have been carried somewhat above the basement complex. That is, these Cambro-Ordovician formations may have been sufficiently competent not only to lift the overburden but also to transmit tangential stress to some degree, and thus control the position as well as the attitude of the folds. This control was naturally aided, and at times directed, by those overlying formations which are also relatively competent.

In general, the position and extent of the entire Appalachian trough is inherited from pre-Cambrian time. The many irregularities, as represented by variations in thicknesses of sedimentary deposits during the different periods, are the results of inequalities in weakness in the basement rocks, and localized overloading because

[1] David White, "Deposition of the Appalachian Pottsville," *Bull. Geol. Soc. Amer.*, Vol. XV (1904), pp. 275–76.

[2] Bailey Willis and Robin Willis, *Geologic Structures* (2d ed., 1929).

of favorable sedimentation. *The structural front corresponds to the thickest zone of sediments from at least early Devonian up through and including the Pottsville—that is to say, the last great weakness of the trough.* It is known that the best development of the remainder of the Pennsylvanian and of the Permian sediments lies west of this zone. This is to be expected, however, as the major Appalachian deformation had already started by that time and presumably the most favorable locus for sedimentary accumulation was moved westward.

A cross-section of the trough of deposition shows a spoon-shaped outline, with the steeper side to the east and the deepest and weakest part of the trough about where the structural front is now located. A series of sediments, if confined in such an unsymmetrically shaped basin and having wide variations in initial dips, should seemingly deform in a characteristic manner when acted upon by a stress from the east or southeast. This is especially true if the stress is transmitted in or close to the basement of the trough. Moreover, the axis of the trough of deposition, the zone of greatest depth, would not only be an initially weak point but would also exert a directive influence throughout the major part of the deformation.

In the initial stage any fold is probably of the incompetent type.

> Its deflection progresses with subsidence during the deposition of the strata in a geosyncline, resulting either in a broad, simple syncline or in synclines and anticlines in alternate pairs. The original distribution of these incompetent folds may be determined in any basin where the beds are exposed to view, by measurements of the variations of thickness . . . . the evidence at hand indicates that, as a rule, the initial, incompetent flexures are convex upward as well as downward, as would be expected since irregularity of subsidence is more probable than regularity. . . . . In the evolution of competent from incompetent folds, it is probable that anticlines first become competent, before synclines, since uplift must commonly be easier than forcible depression . . . . the form of the competent fold will depend upon that of the incompetent flexure and upon the manner of application of the compressive stress.[1]

If we accept the above statements and suggestions as true, then it logically follows that there should be a marked difference in the character of deformation in the overlying beds, on opposite sides of the axis of the trough of deposition. The general parallelism of the structural front with this axis has already been emphasized and the conclusion seems warranted that the observed differences in folding

[1] *Ibid.*

east and west of the front are inherited from initial failures in the trough of deposition. To the east, rotation, overturning, and overthrusting indicates a considerable amount of tangential relief in addition to the major upward relief. To the west of the front and of the weak zone of the trough, the need for tangential relief and rotation seems to have been largely dissipated, and the structures in the overlying sediments are more nearly symmetrical in outline, show very little overthrusting, and are decidedly less intense. However, their very great length, 500 miles for the Chestnut Ridge anticline for example, suggests that the larger structural features are still controlled by lines of weakness in the pre-Cambrian. This probably also applies to the Sequatchie (Valley), Laurel Ridge, and Burning Springs anticlines.

The foregoing suggestions are applicable to the larger features of Appalachian structure. In addition, as has been pointed out before, the position of the competent beds, whether near the surface, in the middle, or toward the base of the section, determines locally or even over a considerable area the dominant type of failure.

THE PEORIAN LOESS AND THE CLASSIFICATION OF THE GLACIAL DRIFT SHEETS OF THE MISSISSIPPI VALLEY

MORRIS M. LEIGHTON
Illinois State Geological Survey

ABSTRACT

The Peorian has always been regarded as the shortest interglacial stage of the glacial epoch. Now it appears from recent new evidence that the Peorian stage was geologically too brief to be regarded as an interglacial stage. Calcareous Peorian loess in the Iowan drift area rests on calcareous Iowan drift, and in Illinois the early Wisconsin ice buried the Peorian loess before it was weathered. Peorian time is recorded primarily by the loess deposit, and the time was so short that we are forced to regard the Iowan ice invasion as the first of the series of invasions of the Wisconsin glacial epoch. This permits, on the one hand, a natural classification of the Wisconsin stage, according to ice centers, and, on the other, a subdivision of Pleistocene time in America that harmonizes with the subdivisions of Europe.

PRESENT CLASSIFICATION

The divisions of the glacial epoch recognized at present by most glacial geologists in North America are as follows:

Wisconsin glacial stage
  Peorian interglacial stage
Iowan glacial stage
  Sangamon interglacial stage
Illinoian glacial stage
  Yarmouth interglacial stage
Kansan glacial stage
  Aftonian interglacial stage
Nebraskan glacial stage

THE SIGNIFICANCE OF THE PEORIAN LOESS

The Peorian loess was formerly called "Iowan loess" by Leverett.[1] After Alden and Leighton showed that the "Iowan loess" around the border of the Iowan drift had been deposited mostly during the early Peorian time,[2] usage changed the name from Iowan to Peorian.

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono. 38* (1896), pp. 153–84.

[2] William C. Alden and Morris M. Leighton, "The Iowan Drift: A Review of the Evidences of the Iowan Stage of Glaciation," *Iowa Geol. Surv.*, Vol. XXVI (1915), pp. 156–64.

In his monograph Leverett did not differentiate the late Sangamon loess from the Peorian loess but called them both Iowan.[1] More recently these have been differentiated on the basis of soil development and a youthful profile of weathering developed on the underlying late Sangamon loess, relations which are preserved widespread in the Mississippi Valley region.[2] A very definite soil and youthful profile of weathering is shown to have been developed on the late Sangamon loess in the type section, before the Peorian loess was laid down.

On the Iowan drift, the late Sangamon loess is absent but some Peorian loess is found. The latter, however, is much thinner than it is around the border of the Iowan area. Apparently much of the loess around the Iowan border was blown from the Iowan drift area before a vegetal covering became effective in holding the surface material, the record being preserved not only in the thickness of the border loess and in the bordering sand dunes but also in the pebble residuum that is fairly general over the Iowan area. In other words, the pebble residuum together with the scanty overlying loess in the Iowan area represent the thick Peorian loess around the Iowan area. The presence of shells of herbivorous land snails of an arboreal type in the border loess show clearly that vegetation of an open woodland character clothed the border area (F. C. Baker) and was a factor in the lodgment of the loess, as was also the rough topography of the Kansan drift.

The Peorian loess locally is thick enough on the Iowan drift to be calcareous, as west of Lisbon, Iowa, and where this is true the underlying drift is calcareous and shows no profile of weathering or soil development.[3] Elsewhere leaching has extended down into the underlying till, fairly commensurate with the thinness of the loess mantle and its texture and the texture of the till. The absence of any deeper color of the upper part of the till as compared with the color of the overlying loess is likewise of significance. It is also true that the Iowan till, where not loess covered, is leached to somewhat

[1] *Op. cit.*, Pl. XI *A* (opp. p. 128).

[2] Morris M. Leighton, "A Notable Type Pleistocene Section: The Farm Creek Exposure near Peoria, Illinois," *Jour. Geol.*, Vol. XXXIV (1926), pp. 167–74.

[3] William C. Alden and Morris M. Leighton, *op. cit.*, pp. 156 and 157.

less depths than the average sections of loess in the bordering Kansan drift area, which is in harmony with the textures of the two formations. The loess, being more porous than the till, should show a greater depth of leaching if both are of approximately the same age.

All of these phenomena indicate that the deposition of the Peorian loess followed immediately the disappearance of the Iowan ice.

As one passes eastward and crosses the Mississippi River, he finds that the Peorian loess on the eastern bluffs reflects the influence of the westerly winds as a carrier and the Mississippi silt flats as another source of supply; likewise when he crosses the Illinois River, both being major streams. And having crossed and recrossed the intervening territory between the Iowan area and the Peoria locality on successive traverses, and having found the same succession of late Sangamon loess below and Peorian loess above, the writer feels confident that the correlation between the Iowan area and the type section is correct. Curator F. C. Baker, of the Museum of Natural History of the University of Illinois, states in personal communication that the fossil faunas are similar. We are therefore ready to consider the relations of the Peorian loess to the early Wisconsin drift and to the loess that overlies the early Wisconsin drift.

The early Wisconsin drift in Illinois, south of the latitude of De Kalb, is generally overlaid by a deposit of loess which attains a thickness of as much as 10 or 12 feet in places, especially close to sources of supply on the leeward side, as, for example, east of Green River and east of Illinois River. Where its thickness exceeds 4–6 feet, the lower part of the loess is not leached, and this calcareous portion rests on unweathered Wisconsin drift, without any sign of a soil zone separating them. Furthermore, this loess is characteristic mainly of the Shelbyville and Bloomington drift surfaces and not of the Marseilles and younger drifts. Therefore it is clearly early Wisconsin in age.

The early Wisconsin loess also accumulated outside of the terminal moraine of the Wisconsin drift and directly overlies the Peorian loess. Therefore the presence or absence of a weathered zone separating the two is important to determine.

NEW DATA ON THE PEORIAN LOESS

The writer and his associates during the past ten years have examined scores of new road cuts that have been made in the course of construction of the state's highway system, and they have found no indication of an interval in any of the sections above the late Sangamon loess horizon.

FIG. 1.—Photograph of the Farm Creek exposure showing the following stratigraphic succession: (*a*) Illinoian till with mature profile of weathering; (*b*) late Sangamon loess with soil and youthful profile of weathering; (*c*) Peorian loess with no profile of weathering; (*d*) early Wisconsin till and gravel with no profile of weathering; and (*e*) early Wisconsin loess with youthful profile of weathering.

These negative results persuaded the writer to re-examine the Farm Creek type section, and in June, 1930, this was done. Fortunately, the western part of the section (Figs. 1 and 2), hitherto too precipitous for careful examination, was found to have become accessible from slumping, and here there is preserved a humous soil horizon, elsewhere cut off by the overriding early Wisconsin ice. This soil possesses the characteristics of a very, very youthful soil, without a profile development. Sublamination shows in the 1*b* hori-

zon, and wood up to 4 inches thick, nearly decayed, occurs in it. Below the soil are numerous cross-sectional splotches of black carbonaceous matter which become less marked toward the bottom. Apparently these are remnants of wood and other vegetal matter which became buried by the wind-blown dust. Fossil terrestrial snail shells, of the rather open woodland type,[1] are present, and these and

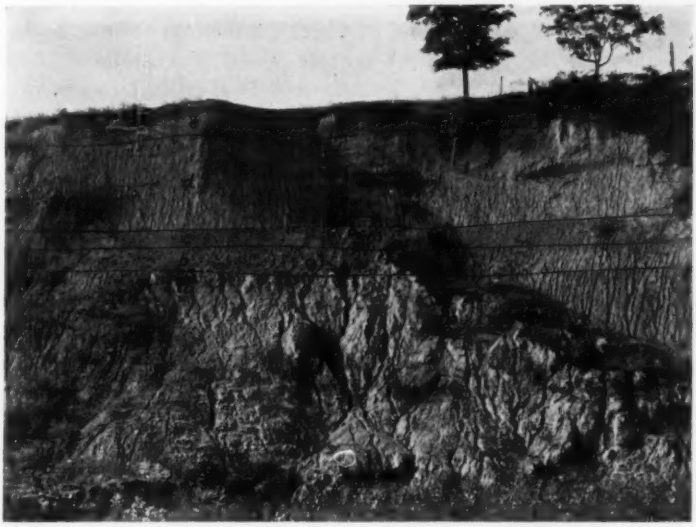

FIG. 2.—A closer view of the exposure shown in Fig. 1

the remains of arboreal vegetation give an impressive view to the scientist of the conditions that prevailed during accumulation and of the original character of our surficial loess deposits before they became oxidized, bleached, and leached. This section, preserved under the protective cover of the early Wisconsin drift, is worth going far to see.

The shells are present from the basal portion to the very top of the soil, showing that there has been no leaching. On the face of the exposure the materials are somewhat rusty colored, but digging back an inch to 6 inches through this mantle, one reaches the bluish-green

[1] Frank C. Baker, curator, Museum of Natural History, University of Illinois, personal communication.

unoxidized materials. The surficial slope weathering is along slope fractures; the plates are unweathered in their interior. In the eastern end of the cut, where slope erosion has removed most of the overlying Wisconsin drift, the loess has been oxidized, the porous loess serving as a water-carrier in contrast to the dense till.

As described in the writer's former paper on this type section, the Peorian loess here rests on the late Sangamon loess (Figs. 1 and 2), which has a soil and youthful profile of weathering, and this in turn on Illinoian till, which has a mature profile of weathering of the mesotil type.[1] The early Wisconsin drift is overlaid by early Wisconsin loess to a maximum thickness of 7 or 8 feet, with a youthful profile of weathering.

No exposures have been seen which are not in harmony with the type section, except at those places where ice scour destroyed a part or all of the Peorian. Along Bureau Creek east of Princeton the Peorian loess is alternately loess and peat; it has no profile of weathering. A new road cut west of Mackinaw, on State Route No. 164, reveals calcareous Peorian loess with an infant soil beneath Wisconsin drift and overlying leached loess of late Sangamon age. Several geological parties this summer scanned exposures for adverse data, in connection with other work, but to no avail.

The history recorded by this type exposure and by regional data seems to be clear. The Sangamon stage was long, much longer than the Recent. A mature profile of weathering was developed, an episode of loess deposition followed, and weathering of this loess ensued. The black soil may represent the accumulation of humus during the Iowan glacial stage when cold-temperate or subarctic temperatures prevailed. Then followed the accumulation of the Peorian loess under arboreal conditions, which continued until the ice of the early Wisconsin substage claimed the area. Loess deposition may have continued in territory beyond the ice front during ice occupancy. At any rate, immediately upon the retreat of the early Wisconsin ice, loess accumulated over the area, especially near sources of supply like the major valley flats of the Illinois and Mississippi, and other rivers. This general distribution of loess

[1] Morris M. Leighton and Paul MacClintock, "Weathered Zones of the Drift-Sheets of Illinois," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 28–53.

ceased before the close of the early Wisconsin, and weathering and erosion set in and has continued until now.

THE IOWAN DRIFT—THE FIRST SUBSTAGE OF THE LAST GLACIAL STAGE

Thus, it will be seen that the Iowan and Wisconsin glacial stages were not separated by an interglacial interval. While the Iowan ice was being melted away and the Labradorean ice center was becoming dominant, the Peorian loess was being deposited. In due time the ice from the Labradorean center crossed the Great Lakes basins, and reached as far south as south-central Illinois.[1] Later the west part of the Labrador field grew from increased snowfall, and here was developed the local Patrician center, subordinate to the Labradorean ice. Subsequently there was sufficient deglaciation and then renourishment by snowfall so that the Keewatin ice field again became important, and it pushed southward to Des Moines, Iowa. The ice from the Labradorean field reached only to the latitude of Milwaukee and Port Huron.

RECLASSIFICATION OF THE IOWAN AND WISCONSIN DRIFTS

In view of the fact that the Iowan drift is the first deposit of the last glacial stage, it must either be known as the early Wisconsin or else the old terms, "early Wisconsin," "middle Wisconsin," and "late Wisconsin," must be dropped. It is nevertheless proposed that the name Wisconsin be retained for the last glacial stage, as it is a well-established name. It is also proposed that the subdivision of the Wisconsin stage be made according to the dominance of the ice fields. This has the advantage of recognizing historical chronology, of placing natural boundaries, and of focusing attention on the fact of shifting dominancy of ice centers. It also permits the listing of the moraines under these divisions and the giving of subordinate places to these minor oscillations.

The nomenclature shown in Table I is therefore proposed. The areal distribution of the Manitoban, Quebecan, and Hudsonian drifts of the Wisconsin stage are shown in Figure 3.

[1] Frank Leverett, "Moraines and Shore Lines of the Lake Superior Region," *U.S. Geol. Surv.* (1929), pp. 154*A*.

The name Manitoban is taken from the province Manitoba, Canada, in which general area the Iowan ice probably had its center of radiation.

TABLE I

Stage	Substage	Moraines
WISCONSIN	Hudsonian (late Wisconsin)	Port Huron–Des Moines and younger
	Quebecan (early and middle Wisconsin)	Shelbyville back to but not including the Port Huron and its correlatives
	Peorian Loess	
	Manitoban = Iowan	

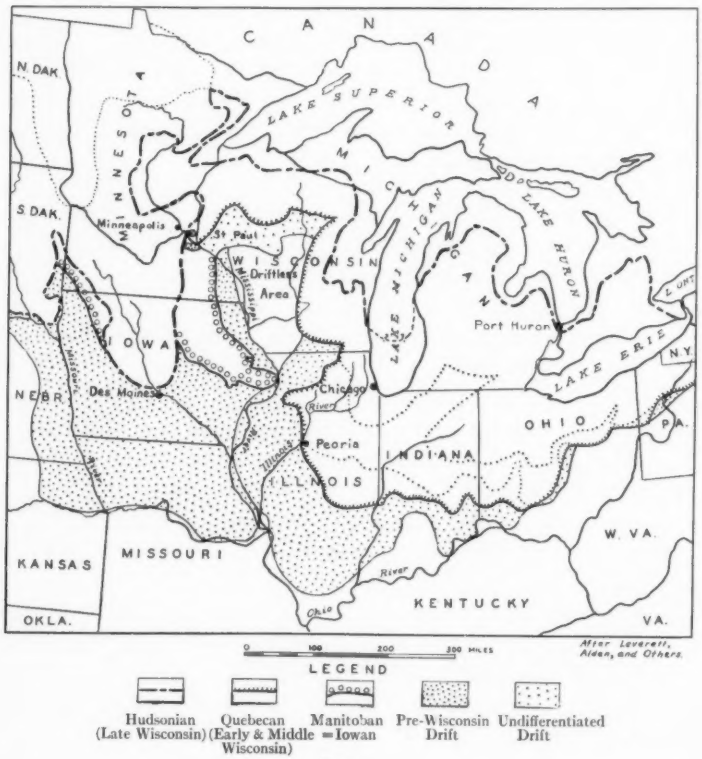

FIG. 3

The name Quebecan is taken from Quebec, a very large area in Eastern Canada, over which general area the ice center was most potent and from which it extended farthest south and southwest during this substage, formerly known as the early and Middle Wisconsin substages. During the latter part of the Quebecan substage the ice field grew westward into the Patrician area and gave rise to a considerable lobe moving south across Lake Superior and to the southwest, depositing the extensive sheet of red drift or Patrician drift of that region.[1] It also gave rise to the notable Green Bay deployment, and retained its power in the East.

The name Hudsonian is chosen for the last substage because the ice fields about Hudson Bay were approximately equally developed.

The use of Canadian names for these substages seems very appropriate in view of the Canadian portion of the continent having furnished the great ice fields that brought into existence the enormous agricultural region of the United States and also in recognition of the contributions of the Canadian geologists to glacial geology.

THE NEW STATUS OF THE AMERICAN AND EUROPEAN CLASSIFICATIONS

The revisions proposed in Table II leave the American classification in harmony with the European.

TABLE II

Stages	In America	In Europe
Fourth glacial	Wisconsin (includes the Iowan)	Würm
Third interglacial	Sangamon	Würm-Riss
Third glacial	Illinoian	Riss
Second interglacial	Yarmouth	Riss-Mindel
Second glacial	Kansan	Mindel
First interglacial	Aftonian	Mindel-Günz
First glacial	Nebraskan	Günz

[1] *Ibid.*, p. 18.

CLASSIFICATION OF IGNEOUS ROCK SERIES

M. A. PEACOCK
University of British Columbia

ABSTRACT

Some rock series cannot be properly classified either as alkalic or as sub-alkalic. To meet this situation a simple extension of the present twofold classification is proposed; this takes the form of a fourfold division into alkalic, alkali-calcic, calc-alkalic, and calcic groups. It is shown, from a partial graphical representation of thirteen rock series, that the silica value at which the curves for total alkalis and for lime intersect (the alkali-lime index) is characteristic of a rock series and is of classificatory value. From a consideration of the curves of the thirteen rock series and their mineral assemblages, limits are suggested for the proposed four groups in terms of the alkali-lime index and of characteristic minerals.

Other classifications of rock series are briefly noticed, and it is observed that they are dependent on a chemical and mineralogical classification. Since an ideal genetic classification is not in sight, it is concluded that a somewhat closely defined, descriptive fourfold grouping on a chemical and mineralogical basis may be more useful than the present rather vague twofold division.

I

A primary division of igneous rock series into two groups, alkalic and sub-alkalic (calc-alkalic, calcic), has long been recognized. Tables contrasting the mineralogical characters of rock types of the two groups have been given by Harker[1] and by Tyrrell;[2] and in general a rock series can be readily placed in this twofold classification.

It has been observed, however, that some rock series lie in a debatable zone between the two groups, where they cannot be properly described either as alkalic or as sub-alkalic. Some rock series of the Arctic Region belong to this class. Thus, in 1918 Holmes[3] wrote: ". . . . the Icelandic volcanic rocks belong neither to a typical 'calc-alkali' nor to a typical 'alkali' series, but share the characters of both." In 1925 the present writer[4] concluded that the Icelandic suite is composite, consisting of an earlier calc-alkali series and a later series of mildly alkalic character; and Cargill, Hawkes, and

[1] A. Harker, *The Natural History of Igneous Rocks* (New York, 1909), p. 91.

[2] G. W. Tyrrell, *The Principles of Petrology* (New York, 1926), p. 137.

[3] A. Holmes, "The Basaltic Rocks of the Arctic Region," *Min. Mag.*, Vol. XVIII (1918), p. 199.

[4] M. A. Peacock, "A Contribution to the Petrography of Iceland," *Trans. Geol. Soc. Glasgow*, Vol. XVII (1925), p. 328.

Ledeboer[1] found that the evidence in Eastern Iceland supports this finding. A more comprehensive study of the Icelandic eruptives, now well advanced, shows that the classification of these rocks is less simple. Without unduly anticipating, it may be said that four series, A, B, C, D, can be distinguished. Series A is fairly clearly calc-alkalic in the present sense; Series B lies in the debatable zone but shows a tendency to the calc-alkalic side; Series C is also in the debatable zone but has distinct alkalic affinities; Series D is an ultra-basic series without alkalic tendencies.[2]

Tyrrell[3] has adopted the appropriate pair of terms, "alkalic" and "calcic" for the primary grouping of igneous rock series; and in simple extension of this terminology the terms "alkali-calcic" and "calc-alkalic," in a restricted sense, suggest themselves as suitable terms to describe rock series, such as the Iceland Series C and B, respectively, lying in the debatable zone. In the belief that such an extension of the present classification might be generally useful, the data of a representative number of described rock series were examined to find natural, acceptable boundaries, if such exist, for the suggested fourfold division. The present note is the outcome of this short study.

II

The character of a rock series is fully displayed in the ordinary variation diagram, in which the values for the oxides are plotted as ordinates against the silica values as abscissas; and in such diagrams the curves for the alkalis and for lime are particularly characteristic. In general, soda and potash vary sympathetically and increase with increasing silica; lime, on the other hand, varies antipathetically to the alkalis and decreases with increasing silica. Consequently, the curve for total alkalis intersects the lime curve in some point in the diagram.

In typical calcic series ranging from about 50 to 75 per cent silica,

[1] H. K. Cargill, L. Hawkes, and J. A. Ledeboer, "The Major Intrusions of South-eastern Iceland," *Quar. Jour. Geol. Soc. London*, Vol. LXXXIV (1928), p. 533.

[2] This grouping of the Icelandic eruptives is provisional, and may not be the one finally adopted. There is no doubt, however, that the Iceland series lie in the transitional zone between alkalic and sub-alkalic in the current sense, and that an extension and closer definition of the present nomenclature is desirable to accommodate them.

[3] *Loc. cit.*

the curve for total alkalis rises from 3 to 4 per cent at the basic end to 7 to 8 per cent at the acidic end, and often shows very little curvature. The lime curve, on the other hand, falls from around 10 per cent in basic rocks to about 1 per cent in acidic rocks, and is likewise nearly straight or somewhat concave upward throughout the greater part of its course. In typical alkali series the curve for the alkalis is systematically higher than in calcic series; furthermore, the curve is strongly convex upward and reaches a pronounced maximum at intermediate silica percentages. The lime curve in alkalic series falls more rapidly than in calcic series and exhibits more strongly pronounced upward concavity. As a result of these relations, the alkali and lime curves in alkalic series intersect at much lower silica percentages than is the case in calcic series, as Holmes[1] has already pointed out.

Since the character of a rock series is expressed in the relations of the alkali and lime curves, the abscissa of the point of intersection of these curves becomes an important index to the character of the rock series, and one which promises to be of value in defining the limits of the proposed fourfold classification. But to have convincing significance, this index must show reasonably systematic relations to the mineralogy of the rock series. To test this, the diagram (Fig. 1) and the accompanying statement of component rock types and essential primary minerals have been prepared. This diagram gives the curves for Na_2O+K_2O (full lines) and for CaO (broken lines), on a silica base, for thirteen described rock series including the three Iceland series, A, B, C. The choice of series represented was determined mainly by accessibility of data; beyond aiming at a fair representation, the curves are those of practically the first thirteen series for which adequate descriptions could be found. From the point of intersection of each pair of curves a perpendicular is dropped to the proper silica axis; the arrowhead thus gives the abscissa of the point of intersection, which we shall call the "alkali-lime index" of the rock series. The thirteen rock series are arranged according to the alkali-lime index, No. 1 (Teneriffe) having the lowest index and No. 13 (Katmai) the highest. Finally, the diagram is traversed by three vertical chain-dotted lines marking the proposed boundaries between the four groups of rock series.

[1] *Loc. cit.*

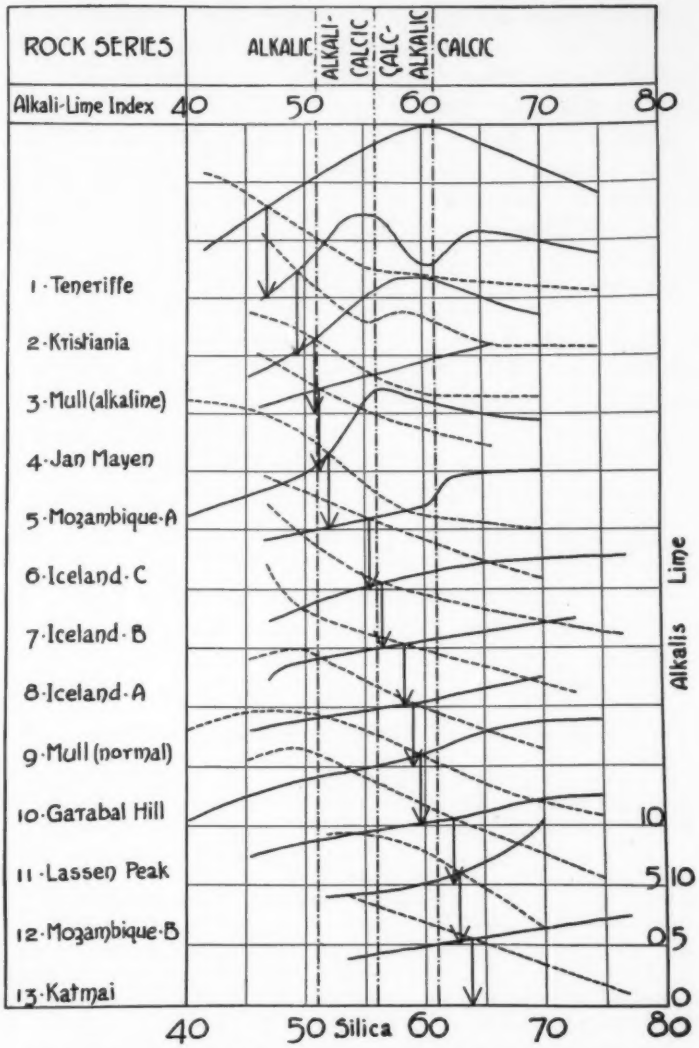

FIG. 1.—Curves for Na_2O+K_2O (full lines) and for CaO (broken lines) for thirteen rock series arranged in four groups according to the "alkali-lime index" (SiO_2 value at which $Na_2O+K_2O=CaO$).

DETAILS OF THE ROCK SERIES REPRESENTED IN FIGURE 1

1. TENERIFFE, CANARY ISLANDS[1]

Rock series.—Basalt[2] (alkali-basalt)—phonolite—trachyte—obsidian.

Mineral assemblage.—Olivine, diopside, aegirine, biotite, magnetite, plagioclase, soda-orthoclase, anorthoclase, sanidine, nepheline, sodalite, nosean.

Alkali-lime index.—46.8.

Classification.—Alkalic.

2. KRISTIANIA (OSLO) DISTRICT[3]

Rock series.—Essexite—lardalite—larvikite (augite-syenite)—akerite (more acid augite-syenite)—nordmarkite (quartz-syenite)—ekerite (soda-granite)—biotite-granite.

Mineral assemblage.—Olivine, augite, aegirine-augite, aegirine, arfvedsonite, biotite, plagioclase, microperthite, anorthoclase, soda-microcline, nepheline, quartz.

Alkali-lime index.—49.3.

Classification.—Alkalic.

3. MULL (ALKALINE MAGMA-SERIES), SCOTLAND[4]

Rock series.—Mugearite—syenite—trachyte—bostonite.

Mineral assemblage.—Olivine, enstatite-augite, augite, aegirine-augite, aegirine, amphiboles allied to arfvedsonite, riebeckite and

[1] A. Logario, "Über die Natur der Glasbasis, sowie der Krystallisationsvorgänge in eruptiven Magma," *Tschermak Min. Pet. Mitth.*, Vol. VIII (1887), p. 440; H. Preiswerk, "Sodalittrachyt vom Pico de Teyde (Teneriffa)," *Centralb. f. Min.*, 1909, p. 396; A. Holmes, "The Tertiary Volcanic Rocks of Mozambique," *Quar. Jour. Geol. Soc. London*, Vol. LXXII (1917), pp. 268–69, Fig. 8.

[2] The basalts do not appear to have been petrographically described. The analyses given by Preiswerk show that they are certainly alkali-basalts, and the large amounts of olivine and nepheline in their norms in Washington's *Tables* warrant the inclusion of these minerals in the mineral assemblage.

[3] A. Harker, *op. cit.*, p. 122, Fig. 25; A. Holmes, *The Nomenclature of Petrology* (London, 1920).

Brøgger's original descriptions of these rocks are not available to the writer; but Harker's variation diagram and list of rock types, together with Holmes's definitions, which are based on Brøgger's descriptions, are adequate for the present purpose.

[4] E. B. Bailey and Others, "The Tertiary and Post-Tertiary Geology of Mull, Lock Aline, and Oban," *Mem. Geol. Sur. Scotland* (Edinburgh, 1924), p. 26, Fig. 4.

barkevikite, magnetite, nepheline ("suspected"), oligoclase, alkali-felspar, orthoclase (?).

Alkali-lime index.—50.8.

Classification.—Alkalic, near the boundary with alkali-calcic.

4. JAN MAYEN (ARCTIC OCEAN)[1]

Rock series.[2]—Trachybasalt—trachyandesite—trachyte.

Mineral assemblage.—Olivine, purple augite, augite, aegirine-augite, hornblende, red-brown biotite, titanmagnetite, ilmenite, plagioclase (labradorite to oligoclase), sanidine, anorthoclase, quartz (very small amount).

Alkali-lime index.—51.2.

Classification.—Alkali-calcic, close to the boundary with alkalic.

5. MOZAMBIQUE A, EAST AFRICA[3]

Rock series.—Picrite-basalt—basalt—tephrite glass—phonolite—sölvsbergite.

Mineral assemblage.—Olivine, titanaugite, aegirine-augite, aegirine, cossyrite, katoforite, arfvedsonite, barkevikite, magnetite, ilmenite, labradorite, andesine, anorthoclase, nepheline (6.6 per cent in phonolite), natrolite.

Alkali-lime index.—52.0.

Classification.—Alkali-calcic.

6. ICELAND C[4]

Rock series.—Trachybasalt—trachyandesite[1]—trachyte—trachyrhyolite.

Mineral assemblage.—Olivine, aegirine-augite, magnetite, bytownite, andesine, albite, anorthoclase, microperthite, soda-orthoclase, orthoclase.

[1] G. W. Tyrrell, "The Petrography of Jan Mayen," *Trans. Roy. Soc. Edinburgh*, Vol. LIV (1926), pp. 747–65.

[2] The full series is: ankaramite—trachybasalt—trachyandesite—trachyte, which give serial relations in a diagram based on percentage of felsic minerals as abscissas (Tyrrell, *ibid.*, p. 761, Fig. 1). On a silica base, ankaramite, with a silica content similar to that of trachybasalt, must be omitted.

[3] A. Holmes, "The Tertiary Volcanic Rocks of Mozambique," *Quar. Jour. Geol. Soc. London*, Vol. LXXII (1917), pp. 233–46, p. 266, Fig. 6.

[4] M. A. Peacock, *op. cit.*, pp. 289–91, pp. 299, 303–6; also new observations.

Alkali-lime index.—55.4.[1]

Classification.—Alkali-calcic.

7. ICELAND B[2]

Rock series.—Olivine-basalt[3]—quartz-hornblende-diorite—hornblende-granodiorite—granophyre—granite-aplite.

Mineral assemblage.—Olivine, augite, hypersthene, soda-diopside (?), hornblende, biotite, magnetite, bytownite, labradorite, andesine, oligoclase, perthite, cryptoperthite, quartz.

Alkali-lime index.—56.4.

Classification.—Calc-alkalic.

8. ICELAND A[4]

Rock series.—Olivine-basalt—basalt—mugearite—rhyolite.

Mineral assemblage.—Olivine, hypersthene, enstatite-augite, purple augite, brown augite, aegirine-augite, magnetite, titan-magnetite, ilmenite, anorthite, bytownite, labradorite, andesine, oligoclase, anorthoclase, quartz.

Alkali-lime index.—58.3.

Classification.—Calc-alkalic.

9. MULL (NORMAL MAGMA SERIES), SCOTLAND[5]

Rock series.—Crinanite and dolerite (Plateau Magma-Type of the Mull authors)—tholeiite and quartz-dolerite (Non-Porphyritic Magma-Type)—craignurite, leidelite and innimorite (Intermediate to Sub-Acid Magma-Type)—granophyre, felsite and rhyolite (Acid Magma-Type).

Mineral assemblage.—Olivine, hypersthene, purple augite, brown augite, hornblende (rare), biotite (rare), iron ore, plagioclase, alkali-felspar, quartz.

Alkali-lime index.—59.0.

Classification.—Calc-alkalic.

[1] The inflexion in the alkali curve is due to the inclusion of trachyandesite in the series. If this rock type were omitted, the alkali curve would rise more rapidly and smoothly and give a lower (more alkalic) alkali-lime index.

[2] H. K. Cargill, L. Hawkes, J. A. Ledeboer, *op. cit.*, pp. 505–39; also new observations.

[3] Petrogenic considerations suggest that olivine-basalt is better placed at the head of this series than gabbro. This change does not affect the alkali-lime index significantly.

[4] A. Holmes, "The Basaltic Rocks of the Arctic Region," *Min. Mag.*, Vol. XVIII (1918), pp. 190–94; M. A. Peacock, *op. cit.*, pp. 276–81; also new observations.

[5] E. B. Bailey and Others, *op. cit.*, p. 14, Fig. 2.

10. GARABAL HILL, SCOTLAND[1]

Rock series.—Olivine-diallage-rock—biotite-diorite—hornblende-biotite-granite—porphyritic-biotite-granite—eurite.

Mineral assemblage.—Olivine, enstatite, augite, diallage, hornblende, biotite, plagioclase, microcline, orthoclase, quartz.

Alkali-lime index.—59.6.

Classification.—Calc-alkalic.

11. LASSEN PEAK[2]

Rock series.—Basalt—andesite—dacite—rhyolite.

Mineral assemblage.—Olivine, hypersthene, augite, hornblende, biotite, magnetite, plagioclase, alkali-felspar, quartz.

Alkali-lime index.—62.4.

Classification.—Calcic.

12. MOZAMBIQUE B, EAST AFRICA[3]

Rock series.—Basalt—hornblende-andesite—groundmass of hornblende andesite.

Mineral assemblage.—Olivine, hypersthene, enstatite-augite, hornblende, biotite, magnetite, ilmenite, labradorite, andesine, orthoclase, quartz.

Alkali-lime index.—62.8.

Classification.—Calcic.

13. KATMAI, ALASKA[4]

Rock series.—Effusive: olivine-basalt—hypersthene-andesite—hypersthene-augite-andesite—dacite—siliceous soda-rhyolite (1912 eruption); Intrusive: Hornblende-andesite-porphyry—hornblende-quartz-diorite—hornblende-biotite-quartz-diorite.

Mineral assemblage.—Olivine, augite, hypersthene, hornblende and biotite (practically absent from the effusives), magnetite, labradorite, andesine, oligoclase, quartz.

[1] J. R. Dakyns and J. J. H. Teall, "On the Plutonic Rocks of Garabal Hill and Meall Breac," *Quar. Jour. Geol. Soc. London*, Vol. XLVIII (1892), pp. 104–21; A. Harker, *op. cit.*, p. 129, Fig. 29.

[2] F. W. Clarke and W. F. Hillebrand, "Analyses of Igneous Rocks, 1880–1896," *U.S. Geol. Sur., Bull. 148*, 1897; A. Harker, *op. cit.*, p. 126, Fig. 28.

[3] A. Holmes, "The Tertiary Volcanic Rocks of Mozambique," *Quar. Jour. Geol. Soc. London*, Vol. LXXII (1917), pp. 246–60, p. 267, Fig. 7.

[4] C. N. Fenner, "The Katmai Magmatic Province," *Jour. Geol.*, Vol. XXXIV (1926), pp. 673–772; N. L. Bowen, *The Evolution of Igneous Rocks* (Princeton, 1928), p. 119, Fig. 36.

Alkali-lime index.—63.8.[1]

Classification.—Calcic.

Inspection of the diagram (Fig. 1) and the accompanying data shows that the order of the rock series as determined by the alkali-lime index is broadly the same as that suggested by the mineral assemblages of the rock series represented. The obviously alkalic series, 1 (Teneriffe) and 2 (Kristiania), have the lowest alkali-lime indices; the most calcic series, 13 (Katmai) and 12 (Mozambique B), have the highest alkali-lime indices; while the three Iceland series (6, 7, 8) with intermediate mineralogical characters, have alkali-lime indices which place them in intermediate positions. The alkali-lime index thus seems to be reliably connected with the mineralogical characters of rock series; and since the index is also sensitive, ranging from 46.8 to 63.8 in the diagram, the promise of its usefulness in classification seems to be fulfilled.

We may now attempt to deduce the best boundaries for the four-fold classification. In general, arbitrary numerical boundaries in petrological classification are properly regarded with strong disfavor; and it is not proposed to lay down inflexible dividing lines delimiting the four groups of rock series on the basis of the alkali-lime index alone. But if a division on this basis can be rationally correlated with significant mineralogical distinctions, the odium attending the division should be greatly mitigated.

The boundary between alkali-calcic and calc-alkalic series clearly should fall between 6 (Iceland C) and 7 (Iceland B)—say at the alkali-lime index value 56. By choosing this boundary, we make Iceland C (trachybasalt—trachyandesite—trachyte—trachyrhyolite) an alkali-calcic series, and Iceland B (olivine-basalt—quartz-hornblende-diorite—hornblende-granodiorite—granophyre—granite-aplite) a calc-alkalic series, which is in keeping with their respective mineral assemblages.

The division between alkalic series and alkali-calcic series is best made at the alkali-lime index where felspathoids cease to appear in appreciable amounts. Series 1 (Teneriffe) and 2 (Kristiania) have abundant felspathoids; in 3 (Mull, alkaline), with the alkali-lime index 50.8, nepheline is "suspected." If we choose the alkali-lime

[1] Bowen's curvilinear modification of Fenner's rectilinear diagram would result in only a slight reduction in the alkali-lime index.

index 51 as the boundary between alkalic and alkali-calcic rock series, then 3 (Mull, alkaline) falls properly near the boundary with felspathoid "suspected" but not determined. This boundary line might seem to misclassify 5 (Mozambique A) as alkali-calcic instead of as alkalic. But the position of Mozambique A with respect to the suggested boundary is interestingly in keeping with Holmes's[1] comment on the character of the series: "It is, therefore, difficult to regard the whole series (Mozambique A) as 'alkaline,' for the alkalis on the right are compensated on the left by high lime and magnesia." These relations between the alkalis and lime are reflected in the alkali-lime index; and the consequent position of the series in the alkali-calcic group, near the boundary with the alkalic group rather than in the alkalic group itself, is quite appropriate.

A natural mineralogical boundary between alkali-calcic and calcic series is not evident. Considerations of symmetry suggest the alkali-lime index 61 as the most suitable point through which to draw the dividing line; and this line properly separates evidently strongly calcic series, 13 (Katmai), 12 (Mozambique B), and 11 (Lassen Peak), from less strongly calcic, therefore calc-alkalic series, 10 (Garabal Hill), 9 (Mull, normal), 8 (Iceland A), and 7 (Iceland B).

Having suggested what appear to be rational boundaries between the four groups of rock series, we may attempt a mineralogical characterization of each group. By inspecting the lists of mineral assemblages, it is found that certain minerals, namely olivine, aluminous pyroxene, biotite, iron and titanium ores, and soda-lime felspars, occur in all series and are therefore non-characteristic. Other minerals again, namely rhombic pyroxene, soda-pyroxene, common hornblende, soda-amphibole, soda-potash felspar, felspathoid, and quartz, occur only in certain series, and are therefore characteristic of the series. Table I gives the normal occurrence (×) or absence (....) of the characteristic minerals in the proposed fourfold classification.

Detailed comparison of the mineral assemblages of the rock series represented with the generalized mineralogical characterization of the four groups in Table I reveals a number of literal contradictions. But it would be surprising, indeed, if such did not occur; and a con-

[1] A. Holmes, "The Tertiary Volcanic Rocks of Mozambique," *Quar. Jour. Geol. Soc. London*, Vol. LXXII (1917), pp. 264–65.

sideration of these exceptions shows that they have but little significance. Modal quartz is absent from the alkali-calcic Series 5 (Mozambique A) and 6 (Iceland C); but in both cases normative quartz was revealed in analyzed specimens.[1] Quartz is present in the alkalic Series 2 (Kristiania); but at the extreme acid end of an alkalic series this is to be expected, although it is better to regard quartz as normally absent in alkalic series, which often do not extend

TABLE I

Characteristic Minerals	Rock Series			
	Alkalic	Alkali-Calcic	Calc-Alkalic	Calcic
Rhombic pyroxene	....	....	×	×
Soda-pyroxene	×	×	?×	....
Common hornblende*	....	....	×	×
Soda-amphibole*	×	×	....	....
Soda-potash-felspar	×	×	×	....
Felspathoid	×	....	....	....
Quartz	....	×	×	×
$Na_2O+K_2O=CaO$ at	51	56		61 per cent SiO_2
		Alkali-lime index		

* In intrusive series.

to extreme acid members. Nepheline and natrolite occur in Series 5 (Mozambique A), classed as alkali-calcic; but the unusual character of this series, and its consequent position in the alkali-calcic group, which is normally free from felspathoid, has already been noticed. Soda-pyroxene fails in the alkali-calcic series 9 (Mull, normal) and 10 (Garabal Hill), whereas it is present in the similarly classified series 7 (Iceland B) and 8 (Iceland A). This raises the question whether soda-pyroxene is to be regarded as normal in calc-alkalic series or not; this is left open by indicating soda-pyroxene in this group thus (? ×).

The fourfold grouping of igneous rock series can thus be expressed in general mineralogical terms Alkalic series may be distinguished from alkali-calcic series by the presence of felspathoid and the normal absence of quartz in the former, while in the latter felspathoid is absent and quartz is present. Alkali-calcic series may be distinguished from calc-alkalic series by the respective absence or presence

[1] A. Holmes, "The Tertiary Volcanic Rocks of Mozambique," *Quar. Jour. Soc. London*, Vol. LXXII (1917), p. 234, norm of sölvsbergite; M. A. Peacock, *op. cit.*, p. 306, norm of soda-trachyte.

of rhombic pyroxene; presence or doubtful presence of soda-pyroxene; absence or presence of common hornblende in intrusive series; presence or absence of soda-amphibole in intrusive series. The mineralogical distinction between calc-alkalic and calcic series is somewhat slender and probably rests more on the relative proportions of characteristic minerals than on their kind. Soda-pyroxene may be present in calc-alkalic series but is absent in calcic series; soda-potash felspar is normally present in the former and absent in the latter.

The relations of the total alkalis to lime are taken as fundamental in the present grouping of rock series; and this seems to be justified since these relations are intimately connected with the character of the felspars of the component rock types, which in turn lies at the root of every classification of igneous rocks. Of the remaining independent chemical variables, soda, potash, ferrous oxide, and titania are the most important. Magnesia does not appear to be an important independent variable, by which is meant that rock series, otherwise comparable, are not found to differ significantly in their magnesia contents. Niggli's threefold classification of rock series into a sodic, a potassic, and a calcic group gives the interrelations of the alkalis equal footing with the relations of the alkalis to lime. But series relatively rich in soda or in potash may occur in any one of the four groups based on the relations of the alkalis to lime, and therefore it seems better to regard the interrelations of the alkalis as of secondary classificatory importance. Similarly, ferrous oxide and titania evidently have secondary status. An adequate characterization of a rock series will thus be given by its position in the alkali-lime classification, as determined by the alkali-lime index and the mineralogical constitution, qualified by a statement regarding the general tenor of soda, potash, ferrous oxide, and titania, if any or all of these depart significantly from normal.

III

Rock series are designated according to two other methods: (1) according to the name of a characteristic component rock type; (2) according to petrographic provinces or magmatic regions. Thus we have the tephrite series or kindred (the term "kindred" implying that the component rock types are genetically related), the trachy-

dolerite kindred, the splite kindred, the andesite kindred, and so forth. Such grouping of rock series is, of course, not independent of a chemical and mineralogical classification; it introduces, furthermore, a new element with the chemical and mineralogical criteria, namely, mode of emplacement. There can be little doubt that the andesite kindred (andesite—dacite—rhyolite) is but the effusive equivalent of the intrusive granodiorite kindred (diorite—granodiorite—granite). Both are associated with belts of recent orogeny; and it would appear that the significant relation is between crustal folding and the production of calcic magma series having certain chemical and mineralogical characters, and that the mode of manifestation of the magma series is a function of subsequent and secondary tectonic conditions.

The grouping of rock series in petrographic provinces is primarily a statement of their regional distribution. But, in addition, the idea of petrographic province usually implies one or both of the following beliefs: (1) that the magma sources are different in different provinces; (2) that the course of magmatic differentiation or of magma formation in a province is controlled by the tectonic events which take place in the province. The first of these is little understood; in regard to the second, there are several significant relationships, but at present there is no prospect of reaching an adequate geotectonic classification of igneous rock series.

An ideal—namely, genetic—classification will not be attained until petrogenic theory has advanced greatly; at present, therefore, it is necessary to adhere to a descriptive classification based on the measurable characters, chemical and mineralogical. Mode of emplacement is a secondary criterion; and regional variation of magma sources and geotectonic influence on magma formation are as yet too little understood to be used as fundamental bases of classification. A somewhat closely defined fourfold classification, based on the relations of the alkalis to lime, may serve better as a basis for a descriptive classification than the current ill-defined twofold grouping.

An objection to the proposed classification might be raised on the ground that the fourfold division obscures a natural dualistic relation expressed in the present twofold grouping. But has the twofold grouping proved to be a natural dualism? Harker's[1] division of igne-

[1] A. Harker, *op. cit.*, p. 90.

ous rocks into two great branches, Atlantic (alkali) and Pacific (calc-alkali), has not found general acceptance; and the reason is not alone that geographic names are unsatisfactory, but that the foundation for the division—namely, the supposed genetic connection between epeirogeny and alkali rocks on the one hand and orogeny and calc-alkali rocks on the other—has not proved secure. The progress of regional petrography and geology tends to show that, while there does seem to be a connection between orogenesis and the formation of calcic magma series with dominant intermediate types, the formation of alkalic magmas is quite independent of tectonic influence. If this is so, there is no natural dualism in Harker's classification.

Again, the various theories which have been put forward to explain the origin of the alkalic rocks all involve processes which may be imposed on the normal process of magma formation in all degrees, producing rock types and rock series with all degrees of alkalic character. Thus Bowen[1] views the problem of the origin of the alkalic rocks as the problem of explaining ". . . . how rocks containing feldspathoids and rocks transitional toward these may be developed from magmas which ordinarily give rise only to quartzose late differentiates." If the production of alkalic rocks results from the assimilation of carbonate rocks, as Daly[2] advocates, this action might clearly be slight or great. Similarly, Gillson's[3] recent suggestion, that alkalic magmas might originate "in the passage of emanations rich in soda and alumina, which albitization phenomena show have occurred," implies a process which might produce rock types and rock series of all degrees of richness in soda. And, more significant than any conclusion drawn from suggested explanations is the obvious fact, borne out by the rather uniform distribution of rock series on the alkali-lime index scale (Fig. 1), that rock series of many degrees of richness in alkalis actually occur.

It appears, therefore, that there is no natural dualistic division of rock series, but rather a gradual progression from normal to extreme alkalic types, a progression which may fittingly be recognized by establishing such groups as may be required for adequate description and classification.

[1] N. L. Bowen, *op. cit.*, p. 235.

[2] R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1924), pp. 412 ff.

[3] J. L. Gillson, "On the Origin of the Alkaline Rocks," *Jour. Geol.*, Vol. XXXVI (1928), p. 471.

GENESIS OF THE ANTHOPHYLLITE DEPOSITS NEAR KAMIAH, IDAHO[1]

ALFRED L. ANDERSON
School of Mines, University of Idaho

ABSTRACT

Anthophyllite as mass-fiber asbestos forms a number of lenticular bodies near Kamiah, Idaho, where it occurs as a replacement of ultra-basic intrusives, particularly dunite. In these bodies the anthophyllite assumes its own characteristic crystal form in replacing the olivine, and occurs as fibers or bundles of fibers arranged in radial groups which on cross-fracture yield rosettes. Associated with the anthophyllite is a minor amount of antigorite, talc, carbonate, and pyrite, typical of mineral assemblages that have been formed by hydrothermal processes. It is believed that the anthophyllite and its associated minerals are the products of hydrothermal metamorphism related to igneous emanations from the Idaho batholith that underlies the deposits at slight depth.

INTRODUCTION

The anthophyllite deposits near Kamiah, Idaho, cited as examples[2] of the occurrence of the amphibole asbestos and mentioned as similar to the mass-fiber variety mined at Sall Mountain, Georgia, afford an interesting study of the origin or genesis of this kind of nonmetallic mineral deposit. Especially do they show the relation to, and dependence of, anthophyllite and other secondary magnesium silicates on the action of magmatic solutions for their origin, and they offer also additional data on the importance of hydrothermal solutions in forming valuable nonmetallic deposits as well as metallic deposits.

These deposits have been worked sporadically since 1909, with a small production during 1909 and 1910, again in 1916 and 1917, in 1921, 1925, and a year or two after, but the demand has always been light because of the lack of nearby markets. The total production has not been assembled.

GENERAL GEOLOGY

The anthophyllite deposits lie at the very margin of the Columbia Plateau about 14 miles east of Kamiah in Idaho County, at an

[1] Published with the permission of the secretary of the Idaho Bureau of Mines and Geology.

[2] J. S. Diller, "The Types, Modes of Occurrence, and Important Deposits of Asbestos in the United States," *U.S. Geol. Surv. Bull. No. 470* (1910), pp. 505–23.

elevation of about 3,100 feet, on the lower western slope of the Clearwater Mountains, but mostly at the base where the basalt of the plateau has been partially removed by erosion. They are enclosed in mica-schists and gneisses of both sedimentary and igneous origin, the latter representing injection gneiss from the Idaho batholith. The sedimentary schists and gneisses are probably derivatives of the Belt series (Algonkian age). They show the results of intense metamorphism, near the asbestos deposits being entirely recrystallized and changed to garnet and cyanite-bearing schists. Apparently much of the metamorphism was accomplished by the intrusion of the Idaho batholith, for not only is much of the country rock an injection gneiss, but the mineral assemblages in the metamorphosed sedimentary rock suggest that much of the change has been induced by transference of volatile constituents from the magma, especially alkalies and water vapor. The schists and gneisses are highly feldspathic and have both muscovite and biotite in addition to garnet and cyanite, as well as several accessories including magnetite, pyrite, and pyrrhotite.

The Idaho batholith, composed mostly of quartz monzonite, but in this region with a wide marginal zone of quartz diorite, is exposed at the surface several miles to the north and east, and the field relations indicate that it underlies the deposits at but slight depth. Apophyses of granite and quartz monzonite from the batholith are numerous in the vicinity of the asbestos deposits, as well as dikes and lenses of pegmatite and aplite, and quartz veins. These acid differentiates are apparently more numerous near the asbestos deposits than elsewhere in the surrounding region.

The asbestos bodies have lenticular shapes and in general conform to the prevailing trend of the enclosing schists and gneisses, pointing mainly in the northwest quadrant and dipping steeply to the northeast or southwest. These have the form and manner of occurrence of intrusive bodies, and, as discussed later, actually represent altered ultra-basic igneous rocks. Whether they owe their present position to folding or were intruded along the bedding of the folded sediments is not entirely known, for the relations beneath the surface are not observable. As some of the bodies are cut by stringers of pegmatite, and as all show evidence of much alteration, probably from the

batholith emanations, their age is pre-Jurassic,[1] for the oldest date assigned the Idaho batholith is Jurassic.[2]

The Kamiah bodies form only a small part of a long belt of ultrabasic intrusives, most of which show stages of alteration to amphibole asbestos, but not to the same degree as near Kamiah. Only the deposits near Kamiah will be described herein.

THE ANTHOPHYLLITE DEPOSITS

GENERAL FEATURES

Most of the anthophyllite deposits are in a comparatively small area of 2 or 3 square miles in the northern part of T. 33 N., R. 5 E., in Idaho County, but minor bodies probably extend for at least 100 miles along the western margin of the Clearwater and Salmon River mountains. The bodies are mainly lenticular and range from minor seams a few feet wide to dikes or lenses as much as 80 feet wide and 200 yards long. More than a dozen bodies greater than 30 feet wide and 100 feet long occur in the area. As the anthophyllite is very resistant to weathering, the bodies tend to form prominent ledges which stand from 10 to 40 feet above the more easily eroded country rock.

STRUCTURE OF THE DEPOSITS

In all the deposits that were examined, the anthophyllite occurs as mass-fiber and forms essentially the whole of the body. The fibers are arranged in small bundles and generally lie in all directions through the rock, but with pronounced tendency to form radial groups which on cross-fracture yield rosettes such as shown in Figure 1. The rosettes are of nearly uniform size in each of the bodies, but vary in size from body to body. The largest measure 6 inches in diameter, while others measure not over 2 inches, but the average is 4 or 5 inches.

Some of the bodies, however, are not composed wholly of anthophyllite, but contain masses or remnants of rock similar to those

[1] These conclusions, which are here briefly abstracted, are to be treated in greater detail in a report now in preparation for the Idaho Bureau of Mines and Geology, to be issued as Pamphlet 34, *The Geology and Mineral Resources of the Region about Orofino, Idaho.*

[2] C. P. Ross, "Mesozoic and Tertiary Granitic Rocks in Idaho," *Jour. Geol.*, Vol. XXXVI (1928), pp. 673–93.

described by Hopkins[1] in the Georgia deposits and explained as the original rock of the deposits not completely altered to anthophyllite. The remnants in the Kamiah deposits range from microscopic granules to masses the size of a man's fist and even larger, distributed more or less uniformly through some of the bodies, but al-

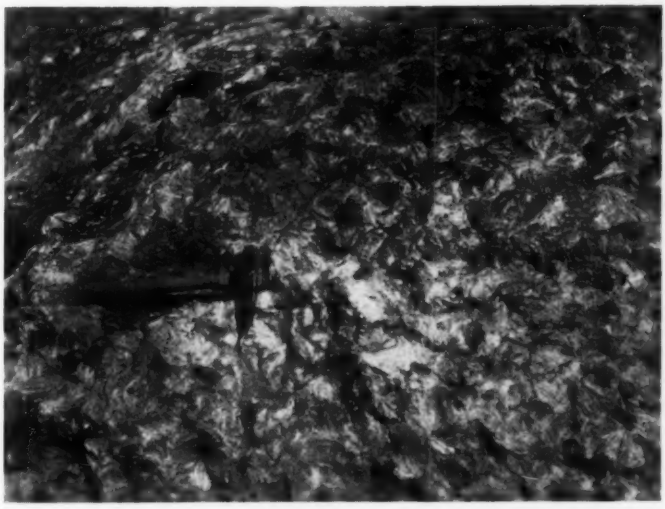

FIG. 1.—Photograph of the anthophyllite to show the characteristic rosette structure of the deposits.

ways forming a very subordinate part as compared with the anthophyllite, and in some of the deposits the remnants are so inconspicuous as to be recognized only in thin section. Many of the granules and masses contain outlines and traces of anthophyllite bundles or rosettes incompletely grown through them.

MINERALOGY OF THE DEPOSITS

Detailed studies of the deposits indicate clearly that they contain minerals of two distinct ages; a group of early primary minerals as represented by the remnants of rock mentioned in the foregoing,

[1] O. B. Hopkins, "A Report on the Asbestos, Talc, and Soapstone Deposits of Georgia," *Geol. Surv. of Georgia Bull. No. 29* (1914), pp. 41–64, 103–5.

and a group of later minerals that have developed by replacement, the second group including the anthophyllite.

Primary minerals.—The primary minerals of the deposits, as determined from microscopic studies of the residual granules and masses, consist essentially of olivine with accessory magnetite, chromite, and pale yellowish brown spinel (picotite). The accessories are sufficiently abundant to give the olivine masses a distinct grayish color, although a dark olive-green tinge persists. The magnetite and chromite occur as scattered grains and crystals in the olivine, in cleavage cracks, and in veinlets somewhat later than the olivine. The picotite is sparsely distributed within the olivine, although some of it is more or less related to cleavage lines. The olivine occurs in interlocking grains, the texture and the minerals indicating that the remnants have the composition of dunite, and, as they are scattered more or less uniformly throughout the body, that the original intrusive was dunite. Elsewhere in the region the intrusives contain enstatite, which indicates that some of the bodies should be classed as harzburgites, but curiously these have given very little mass-fiber anthophyllite, most of it consisting of slip-fiber, and none of it being of commercial value. It is possible, however, that enstatite might occur in some of the Kamiah deposits, for all bodies were not examined microscopically.

Secondary minerals.—The list of secondary minerals is not long, and arranged in order of development consists of antigorite, kammererite (?), anthophyllite, talc, magnesite (?), and pyrite. Of these, only the anthophyllite and talc are noticeable in the outcrop.

Antigorite: The thin sections reveal only very minor and variable amounts of the lamellar variety of serpentine, antigorite, this mineral clearly replacing the olivine. It in turn is replaced by each of the others. The alteration of the olivine to antigorite is apparently irrespective of cleavage cracks or crystal boundaries of the olivine. Curiously, the antigorite is relatively free from magnetite and chromite, minerals so abundant in the olivine, a relation which suggests that the iron was removed by the solution which caused alteration of the olivine.

Kammererite (?): Several crystals of kammererite (?) were noted in one of the thin sections where it shows replacement of the olivine.

Perhaps the aluminum that is necessary to form kammererite was obtained from the picotite, and perhaps even much of the iron and magnesium. The relation to antigorite could not be determined as the two were not found in contact, but they are probably nearly contemporaneous, for they show replacement by the same minerals.

Anthophyllite: The occurrence of anthophyllite as fibers and needles in bundles arranged in radiating groups has been mentioned.

FIG. 2.—Photomicrograph showing the fibrous anthophyllite (*A*) penetrating and replacing the olivine grains (*O*), irrespective of crystal boundaries and cleavages. ×32.

The fibers are brittle, readily breaking into short lengths and splitting into fine threads that are polygonal in cross-section. In luster they are dull to vitreous, often having a nearly glassy appearance. The weathered anthophyllite is grayish or white, usually very little iron stained. It is probable that the anthophyllite has a very low iron content and is essentially a magnesium silicate ($MgO \cdot SiO_2$).

The replacement of olivine by anthophyllite is as striking in thin sections as in the outcrop where the rosettes penetrate the larger remnants of olivine. The direct alteration of olivine to anthophyllite,

as observed in thin section, is not controlled in the slightest degree by the physical properties of the olivine; and thus the needles of amphibole pierce the olivine grains without regard to their boundaries, cleavages, or cracks, as shown in Figure 2. They extend continuously from one olivine grain to another, so that a single needle or bundle of needles may pierce consecutively as many as five or six or more differently oriented olivine individuals. The development of

FIG. 3.—Photomicrograph showing bundles and needles of anthophyllite (*A*) replacing both antigorite (*S*) and olivine (*O*). ×32.

the amphibole needles and bundles in both size and number gradually leads to the diminution in the amount of olivine until the rock is converted from a dunite into amphibolite in which olivine is entirely absent. Not only does the anthophyllite replace the olivine, but it replaces the antigorite and kammererite (?) as well, the needles and bundles of needles passing from these to the olivine with no apparent change in quantity or in ease of replacement, as illustrated in Figure 3. Although the anthophyllite is usually very finely fibrous, some of it occurs in coarse crystals, always with an excellent

prismatic cleavage, and with cross-fractures. The chromite and magnetite, which are present in some abundance in the remnants of olivine, are mainly absent from the anthophyllite or are in much less quantity.

In other localities where enstatite is a primary mineral, the anthophyllite replaces the pyroxene with much the same relations as in the case of olivine.

Talc: The talc is much subordinate to the anthophyllite, but it may readily be distinguished in the outcrop where it occurs in small glistening flakes in the fibrous bundles, some between the anthophyllite fibers and some apparently merging with the anthophyllite. In a few places, the talc forms plates 2 or 3 inches across.

The talc, in thin section, shows replacement of the anthophyllite, antigorite, and olivine, a single flake or plate replacing one or all three, but the alteration has not been extensive, and the talc present does not interfere with the use of the anthophyllite. The replacement of anthophyllite and antigorite is shown in Figure 4.

Magnesite (?): A carbonate, probably magnesite, occurs in very small amount in some of the sections as small grains and irregular masses, apparently younger than the other minerals or about contemporaneous with the talc. Its chief rôle is that of a cementing medium, but it may show slight replacement of the other minerals. Some of the magnetite and chromite that appear to replace the olivine might have been introduced by the solutions which deposited the carbonate.

Pyrite: Pyrite is also a very minor mineral in the deposits, but its occurrence is of interest. It forms a few scattered irregular grains and also cubes replacing all the minerals described, except possibly carbonate. Crystals may be noted as embayments across cleavage cracks in the olivine, also between and across needles of anthophyllite, and as replacements of the antigorite and talc. The pyrite is probably the last mineral to be formed in the deposit.

Process of alteration.—The study of the asbestos deposits indicates clearly that the anthophyllite and its associated minerals have formed by replacement of the olivine in the original dunite, the minerals replacing the olivine in fairly well-established sequence. There remains, however, to establish the process and cause of this

replacement. Such processes and reactions were worked out long ago by Van Hise.[1] The alteration of olivine to serpentine (antigorite) involves either the addition of silica and water or the removal of magnesia by solutions carrying carbon dioxide. Expressed by chemical equations, the first reaction might be represented by the follow-

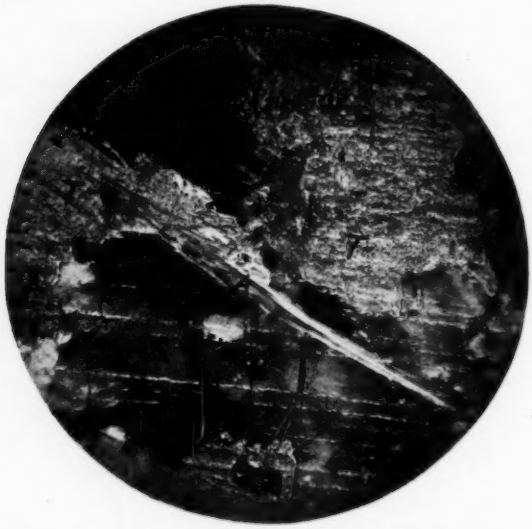

FIG. 4.—Photomicrograph showing talc (*T*) replacing antigorite (*S*) and a bundle of anthophyllite fibers (*A*). Note how the anthophyllite crosses the antigorite lamellae whereas the talc in part is directed along the lamellae boundaries. ×32.

ing simple equation, the iron present in the olivine and serpentine being disregarded:

(1) $$3[2MgO \cdot SiO_2] + SiO_2 + 4H_2O = 2[3MgO \cdot 2SiO_2 \cdot 2H_2O]$$
Olivine — Serpentine

If the alteration had been by solutions carrying carbon dioxide, the reaction might be expressed as in equation (2).

(2) $$2[2MgO \cdot SiO_2] + CO_2 + 2H_2O = 3MgO \cdot 2SiO_2 \cdot 2H_2O + MgCO_3$$
Olivine — Serpentine — Magnesite

[1] C. R. Van Hise, "A Treatise of Metamorphism," *U.S. Geol. Surv. Monograph No. 47* (1904), pp. 270, 282, 310–11.

However, as magnesite has not been formed during the alteration wherein olivine was partially replaced by serpentine, the second equation does not represent the reaction, but the alteration has apparently been by siliceous solutions.

Replacement of olivine (perhaps with spinel) by kammererite $5(Mg,Fe)O \cdot Al_2O_3 \cdot 3SiO_2 \cdot 4H_2O$ also involves the addition of water and silica, but as kammererite (?) plays such a minor rôle in the alteration no equations will be written.

The alteration of olivine to anthophyllite also involves the elimination of a part of the magnesia (and iron) or an addition of silica. In the former case, the solutions carrying carbon dioxide could remove the excess magnesia to yield magnesite as a product as indicated in equation (3).

(3) $$\underset{\text{Olivine}}{2MgO \cdot SiO_2} + CO_2 + H_2O = \underset{\text{Anthophyllite}}{MgO \cdot SiO_2} + \underset{\text{Magnesite}}{MgCO_3} + H_2O$$

Again, however, as magnesite does not occur as a product in this stage, the alteration has probably been by the addition of silica as expressed in equation (4).

(4) $$\underset{\text{Olivine}}{2MgO \cdot SiO_2} + SiO_2 = \underset{\text{Anthophyllite}}{2MgO \cdot SiO_2},$$

Water does not enter into combination in this equation nor in equation (3), although the solutions which brought in the carbon dioxide or silica were undoubtedly aqueous. Perhaps hydrous minerals were not stable at the temperatures that prevailed during this stage of the alteration.

As the antigorite also is replaced by anthophyllite, the reaction should be expressed by an equation such as (5), a molecule of silica

(5) $$\underset{\text{Serpentine}}{3MgO \cdot 2SiO_2 \cdot 2H_2O} + SiO_2 = \underset{\text{Anthophyllite}}{3MgO \cdot SiO_2} + 2H_2O$$

being added and water being lost. The formation of an anhydrous mineral from a hydrous is a reversal of the usual order, but it perhaps might be explained by increased or high temperatures.

The replacement of either olivine, antigorite, or anthophyllite by talc can again involve either the removal of magnesia by carbon dioxide or the addition of silica and water. As magnesite does appear

to be in association with the talc, carbon dioxide probably plays a rôle in this process. The reactions expressed for the alteration of anthophyllite to talc (those of antigorite and olivine to talc may readily be shown in similar manner) are given in the following equations. The reactions with carbon dioxide are given in equation (6) and this probably represents the main reaction, the amount of

(6) $4[MgO.SiO_2]+CO_2+H_2O=3MgO\cdot 4SiO_2\cdot H_2O+MgCO_3$
Anthophyllite — Talc — Magnesite

magnesite present in the deposits being about what might be expected from the quantity of talc produced. However, there is a possibility that the carbonate represents deposition from alkaline solutions and is less directly related to talc formation. The talc might also have formed from the anthophyllite by addition of water and silica as indicated in equation (7), and some may have done so, but

(7) $3[MgO\cdot SiO_2]+H_2O+SiO_2=3MgO\cdot 4SiO_2\cdot H_2O$
Anthophyllite — Talc

as pyrite has been subsequently introduced it is probably more reasonable to assume that the alkaline solutions that carried it in also attacked the earlier minerals, forming talc as outlined in equation (6).

Thus the nature of the reactions and the general sequence of events suggest that the alteration has involved the addition of water and silica in an early stage, of silica alone in later, and of water, carbon dioxide, and sulphide in the final stage.

Source of the solutions.—The development of anthophyllite and other amphiboles from olivine has been described by Van Hise[1] as deep-seated reactions in the zone of anamorphism, the alteration to serpentine and talc, as reactions in the zone of katamorphism, both in the belt of weathering and the belt of cementation. More recently such changes as described in the foregoing have been considered the result of hydrothermal alteration.

Anthophyllite has been cited as a mineral formed by hydrothermal processes in the Webster dunite bodies[2] in North Carolina, in

[1] C. R. Van Hise, *op. cit.*, p. 311.

[2] C. S. Ross, "Is Chromite Always a Magmatic Mineral?" *Econ. Geol.*, Vol. XXIV (1929), p. 642.

which zones of anthophyllite and talc surround the bodies, while within the dunite are sparsely disseminated grains of actinolite, kammererite, talc, and diallage. Locally, many small veins cut the dunite and these contain anthophyllite, tremolite, biotite, talc, chlorite, vermiculite, serpentine, and kammererite. Ross states that most of these disseminated and vein minerals are typical of mineral assemblages that have been formed by hydrothermal processes.

In the Rainy Creek district of Montana, Pardee and Larsen[1] describe the occurrence of the amphibole related to tremolite as an alteration of a pyroxenite mass changed by the hydrothermal metamorphism attending the widespread action of hot solutions of unusual character from an intrusion of alkaline rocks.

Gillson[2] has also concluded from his study of the talc deposits that the type of solutions that formed talc, whatever was the original rock replaced, first formed an amphibole, a serpentine or chlorite, and later talc, and in some deposits magnetite and pyrrhotite at about the same time as the talc or even later. He believes that in many cases, if not in all, these solutions, which caused the alteration, were emanations from granitic or dioritic rocks, or from the acid differentiates of basic intrusives, and that the solutions were hot, alkaline, and were at first siliceous and carried iron, calcium, and some aluminum in addition to magnesium, later becoming less siliceous and rich in magnesium.

The Kamiah deposits thus might well be considered the product of hydrothermal processes, formed by the action of magmatic waters at first mainly siliceous, but becoming richer in carbonates and sulphides in declining stages, the source of the solutions from the Idaho batholith that underlies the deposits at but slight depth. That magmatic solutions especially rich in water and silica invaded the area of asbestos rocks is evident from the abundance of aplites, pegmatites, and quartz veins in that immediate vicinity. Perhaps the hydrothermal metamorphism is much like the contact meta-

[1] J. T. Pardee and E. S. Larsen, "Deposits of Vermiculite and Other Minerals in the Rainy Creek District, near Libby, Montana," *U.S. Geol. Surv. Bull. No. 805-B* (1928), pp. 17–28.

[2] J. L. Gillson, "Origin of Vermont Talc Deposits," *Econ. Geol.*, Vol. XXII (1927), pp. 246–87.

morphism described by Gillson[1] in the Pend Oreille district of north Idaho, where the metamorphism of the invaded rocks was produced by a long procession of solutions that came out from the igneous rock (a supposed outlier of the Idaho batholith), these solutions rich in alkalies at first but becoming more siliceous and in the last enriched in sulphides and carbonates. The character of the metamorphosed sediments in the Kamiah district also indicates that here, too, the earliest solutions were rich in alkalies but these caused no appreciable effect on the olivine bodies.

SUMMARY AND CONCLUSIONS

In summary, it is believed that the anthophyllite deposits near Kamiah, Idaho, are a replacement of dunite bodies, the anthophyllite and its associated minerals being the products of hydrothermal metamorphism or alteration related to igneous emanations. The dunites of uncertain, but of pre-Jurassic age, were invaded by the Idaho batholith and from this later great body came the magmatic solutions which permeated through the ultra-basic intrusives replacing the olivine by an assemblage of secondary minerals, including anthophyllite.

The solutions in early stages had high temperatures (hydrothermal) and were mainly siliceous, and as they penetrated the dunite bodies added silica and in some parts water to change the olivine to fibrous amphibole (anthophyllite) and to serpentine (antigorite). Perhaps the high temperatures and great pressures that existed during the early stages did not favor extensive formation of serpentine with its possible lower temperature of formation, and although a little was formed when the solutions first encountered the relatively cool olivine most of it was soon replaced by the more stable amphibole. The same reasoning holds for the kammererite. During later stages the solutions became progressively cooler, probably more aqueous, and richer in carbon dioxide and also in sulphides. The anthophyllite and serpentine, no longer stable under these changed conditions, were attacked and with the olivine were partially replaced by talc, apparently with the deposition of minor amounts of

[1] J. L. Gillson, "Contact Metamorphism of Rocks in the Pend Oreille District, Northern Idaho," *U.S. Geol. Surv. Prof. Paper No. 158-F* (1929), pp. 111–21.

carbonate. Sulphides, as represented by pyrite, were soon deposited by replacement of the earlier minerals, and this closed the chapter in the hydrothermal alteration of the dunite bodies.

The sequence of alteration, as outlined, shows a marked similarity to the sequence of events that are recorded in the history of many of the quartz veins in the region, usually early deposition of quartz followed later by sulphides and carbonates, indicating that here, too, the early solutions were highly siliceous, but became enriched in carbonates and sulphides with time and lower temperatures. In the case of the asbestos deposits, however, the magmatic solutions were not wholly confined to fissures forming veins, but permeated through the surrounding rock, perhaps in the main emanating directly from the magma and, in encountering the dunite bodies, causing the changes described.

COOKE'S CORRELATION OF COASTAL TERRACES: A DISCUSSION

RICHARD FOSTER FLINT
Yale University

In a recent paper[1] C. Wythe Cooke has brought together widely scattered data on the terraces along the Atlantic and Gulf coasts of North America, and combining them with his own extensive work on these features, he has drawn far-reaching conclusions worthy of very serious consideration. By filling in the gaps between studies in restricted areas, Cooke has discovered that six terraces, standing respectively at 25, 65, 95, 160, 215, and 265 feet above sea level, are continuously traceable from Florida to New Jersey, each maintaining its own level throughout the entire distance. He argues with reason that this horizontality is much more likely to have been brought about by successive shifts of sea level than by successive uplifts of the land entirely uncomplicated by warping. He then urges the belief that the terraces were formed during successive nonglacial and interglacial epochs, in descending order as follows: Preglacial, Aftonian, Yarmouth, Sangamon, Peorian, and mid-Wisconsin. Realizing that such a correlation strongly implies the presence of terraces at similar levels on other coasts, Cooke cites published references to terraces at somewhat similar levels along the coasts of South Africa and France. He also examines references to the North American coast north of New Jersey, notably a discussion of the Connecticut Valley by the writer.[2] This discussion describes a series of sixteen horizontal terraces built up in temporary lakes marginal to stagnant residual masses of the last ice sheet, and controlled by spillways. Cooke suggests a correlation of the five lowest terraces with five of the six marine terraces in the southeastern states. He says:[3]

> The terraces below 265 feet in the Connecticut Valley, along Hudson River, and on Long Island, may have been formed at the same time and in the same manner as those south of the terminal moraines, but may have been later over-

[1] "Correlation of Coastal Terraces," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 577–89; see also "Pleistocene Seashores," *Jour. Wash. Acad. Sci.*, Vol. XX (1930), pp. 389–95.

[2] "Pleistocene Terraces of the Lower Connecticut Valley," *Bull. Geol. Soc. Amer.*, Vol. XXXIX (1928), pp. 955–84.

[3] *Op. cit.*, p. 581.

ridden by the Wisconsin ice sheet and veneered with glacial deposits. This suggestion is not necessarily at variance with Flint's interpretation, for lakes may have been dammed up by remnants of the Wisconsin ice to altitudes controlled by spillways over pre-existing terraces.

If the five lowest spillways referred to by Cooke operated successively at five levels just high enough to veneer five pre-Wisconsin terraces with lacustrine deposits, without destroying the topographic unity of each terrace, the coincidence involved would be difficult for many to accept. Actually no one need even consider the implied coincidence, since the lacustrine deposits at issue do not represent veneers over pre-existing terraces. Hundreds of exposures show that they are composed of solid gravel, sand, silt, and clay extending from top to bottom of each terrace form, indicating uninterrupted deposition without unconformity of any kind.[1] Continuous sections more than 200 feet thick are plainly exposed. In addition to the fact that all the terraces in Connecticut are late glacial in age and constructional throughout their entire thickness, it is significant that these forms occur only along the sides of the valleys and are entirely absent from the seaward slopes of the interfluves, where marine terraces, including those of the southeastern states, characteristically reach their best development.

It is to be hoped that Cooke's thesis will receive the widespread attention its ingenuity deserves, and that investigators familiar with raised shore lines on other coasts will be stimulated to contribute data bearing on the problem. Some coasts, like those of France and South Africa cited by Cooke, yield evidence that may prove favorable to the hypothesis. In other regions, such as Great Britain, the Pacific Coast of North America, and the lower Nile Valley,[2] the terrace levels are definitely out of harmony with it. But, in any case, no help need be expected from southern New England, whose crystalline rocks are highly resistant to the development of marine terraces and whose surface has been modified by at least two glaciations. The case for the origin of the Coastal Plain terraces must rest on other evidence.

[1] R. F. Flint, "The Stagnation and Dissipation of the Last Ice Sheet," *Geog. Rev.*, Vol. XIX (1929), pp. 256–89; see also "The Glacial Geology of Connecticut," *Conn. Geol. and Nat. Hist. Surv. Bull. 47* (1930), esp. pp. 84–87.

[2] K. S. Sandford and W. J. Arkell, "First Report of the Prehistoric Survey Expedition," *Oriental Institute Communications* (University of Chicago, 1928), No. 3, pp. 5–17.

REVIEWS

The Pre-Illinoian Pleistocene Geology of Iowa.[1] By GEORGE F. KAY AND EARL T. APFEL. *Iowa Geological Survey*, Vol. XXXIV. Des Moines, Iowa, 1929. Pp. 289; figs. 63; pls. 3.

In this paper the authors present the results of their extended field and laboratory studies of the older glacial and interglacial deposits of Iowa, together with a map of the drift sheets which, for the first time, shows the approximate distribution of the Nebraskan drift where overlying deposits, excepting loess and alluvium, have been cut away.

Following summary statements on the older rock formations and the drainage and analyses of the present types of topography in the state, a history is given of the numerous investigations and of the several changes that marked the development of the present classification of the Pleistocene deposits of the state, which is as follows:

Glacial Stages	Interglacial Stages
Wisconsin	
	Peorian
Iowan	
	Sangamon
Illinoian	
	Yarmouth
Kansan	
	Aftonian
Nebraskan	

Concerning a return to the original usage of the names Kansan and Iowan, such as has been favored by some geologists, the authors state as their opinion (pp. 283–84):

> Regardless of the weight of evidence with respect to priority of the terms Kansan and Iowan for the two oldest drifts, it would seem to be best from the standpoint of long usage to continue to use the names as they have now been used for so long a time. . . . . To revert now to the original usage would result in endless confusion and most serious inconvenience.

This opinion is one in which most geologists probably will acquiesce, even if they do not all heartily concur with it.

There was in Tertiary time the development of the Dodgeville pene-

[1] Review published by permission of the director, U.S. Geol. Surv.

plain in northeastern Iowa and adjacent areas, followed by its uplift and erosion to a depth of about 200 feet and the development of the Lancaster peneplain. It is found that the earliest (or Nebraskan) ice advanced over a maturely dissected surface of about 400 feet of relief. When the second (or Kansan) ice advanced the relief is thought to have been somewhat less. The Nebraskan drift is said not to have been found in Iowa much below the Lancaster peneplain. Mr. Frank Leverett has reported what he regards as Nebraskan drift buried beneath Kansan drift at such relatively low elevations as to lead him to think the Mississippi River had cut to levels even below its present bed before the earliest ice invasion. Post-Nebraskan erosion has given a relief in places of 500–600 feet below the Lancaster peneplain. Some of the streams are now flowing, in places, about 200 feet above buried rock floors.

Particular stress is laid on the very important matter of the gumbotils, the thoroughly weathered upper parts of each of the oldest three drift sheets. They are regarded as products of periods of chemical modification, before the dissection or burial of these several drifts, much longer than those periods during which the later drifts have been subjected to similar action. The gumbotils are regarded by the authors as the most satisfactory criteria that have been found for differentiating the older drifts in Iowa. The gumbotils seem to the present writer to have required somewhat specialized conditions for their development, and their use as such criteria should proceed with caution outside of Iowa and Illinois where they have, thus far, been most critically studied. Similar gumbotils may be found in adjacent parts of Minnesota, Nebraska, Kansas, and Missouri. The gumbotils should, perhaps, not be regarded as precise indicators in the projection of stratigraphic horizons in the Pleistocene series. The evidence in hand is said to indicate clearly that both the Kansan and the Nebraskan till extended into eastern Nebraska.

The characteristics of each of these drifts, the unleached and unoxidized tills, are presented, and there is detailed description of each of the three successive zones of modification: the oxidized and unleached zones, the oxidized and leached zones, and the gumbotils.

The first, or Aftonian, interglacial stage is, it is stated, to be measured in hundreds of thousands of years. The second, or Yarmouth, interval was also very long. Gumbotil, peat, and related materials are regarded as the most widespread deposits indicative of these interglacial stages. The famous Aftonian gravels, including the fossiliferous gravels of western Iowa, are interpreted not as interglacial but as partly Nebraskan and partly Kansan in age. The authors write:

At the present time it is impossible to state whether the gravels in which the mammalian remains have been found are associated with Nebraskan till or with Kansan till since . . . . it has not been possible thus far to differentiate Nebraskan till from Kansan till except where the relationships of the till to gumbotil, the age of which is known, have been established.

Dr. O. P. Hay, who has studied the mammalian fossils from these gravels of western Iowa, is of the opinion that these mammals could not have lived in the immediate vicinity of an ice sheet. On the other hand, the authors state, W. D. Matthew believes that in determining the age of gravels and sands, stratigraphic evidence can be more safely followed than fossil evidence.

Some consideration is given to the relative ages of the Iowan and Illinoian drift sheets in connection with description of the Loveland loess. The authors state, in part (pp. 278–90):

The Loveland formation rests upon the eroded surface of the Kansan gumbotil plain. The Loveland interval, therefore, began not earlier than late Yarmouth time. . . . . As the loess resting upon the Loveland is in part, at least, Peorian in age, the close of the Loveland interval preceded that interglacial stage. . . . . The deposition of a part of the Loveland may have taken place during Yarmouth time, but the exact extent to which the Loveland formation represents that interglacial stage has not yet been determined. . . . . The finding of the Loveland loess beneath Iowan till dates it as certainly older than the formation of that till.

When Dr. Kay, in an earlier paper (*Science*, Nov. 16, 1928), described the Loveland as "much younger than the Illinoian glacial drift and older than the Iowan glacial drift," Mr. Leverett (*ibid.*, May 24, 1929) questioned the differentiation of the Loveland outside the Illinoian border from a loess on eroded Kansan drift beneath the Illinoian drift.

In a résumé of the glacial stages the authors state: "There seems to be no reasonable doubt, when all the evidence is fairly balanced, that there are in Iowa remains of five distinct glacial stages and of four distinct interglacial stages."

In the opinion of the reviewer, this paper by Mr. Kay and his assistant, Mr. Apfel, is an important and valuable contribution to the knowledge of the Pleistocene glacial and interglacial deposits of North America. It is well written and should be widely read by those interested in Cenozoic geology.

WILLIAM C. ALDEN

A Textbook of Geology. By L. V. PIRSSON and CHARLES SCHUCHERT. Part I: *Physical Geology*, by the late L. V. PIRSSON. Third edition revised by WILLIAM M. AGAR, ALAN M. BATEMAN, CARL O. DUNBAR, RICHARD F. FLINT, ADOLPH KNOPF, and CHESTER R. LONGWELL; revision edited by CHESTER R. LONGWELL. New York: John Wiley & Sons, 1929. Pp. vii+488; figs. 322. $3.75.

The new Pirsson is a revision and must be judged as such, but the six co-operating members of the Yale faculty have done a most thorough piece of work. Previous editions used a primary division into "Dynamical Geology" and "Structural Geology." This has been given up. The work of the various geologic agencies is still treated before rocks or structure, but the chapters are rearranged as shown in the following list: (i) "The Scope and Method of Geology" (Longwell); (ii) "A General View of the Earth" (Knopf); (iii) "The Atmosphere; Weathering and Soils" (Bateman); (iv) "Rain and Running Water "(Flint); (v) "Glaciers and Glaciation" (Bateman); (vi) "Subsurface Water" (Agar); (vii) "Lakes and Swamps" (Flint); (viii) "Oceans and Seas" (Dunbar); (ix) "Sedimentary Rocks" (Dunbar); (x) "Volcanoes and Volcanism" (Knopf); (xi) "The Igneous Rocks" (Knopf); (xii) "Warping, Folding, and Fracturing in the Earth's Crust" (Longwell); (xiii) "Earthquakes" (Longwell); (xiv) "Metamorphism and Metamorphic Rocks" (Knopf); (xv) "Nature of the Earth's Interior" (Longwell); (xvi) "The Origin and History of Mountains" (Longwell); (xvii) "Land Forms" (Flint); (xviii) "Ore Deposits" (Bateman); (Appendix A) "Minerals" (Agar); (Appendix B) "Chronology of Earth History" (Agar). It can be seen that an attempt has been made to have each reviser deal with his field of particular interest. Thus the revision is to a considerable extent the work of specialists. That the whole is so smoothly co-ordinated must be accounted a triumph for joint effort.

The revision preserves the balance among the various divisions of physical geology which was so notable in the original Pirsson. In particular, difficult and technical subjects are not minimized. As a result, some may feel that in places the interest of the general student is sacrificed for the benefit of the prospective geologist. On the other hand, the reviewer considers that incisive and critical treatment of such things as metamorphism and the crystallization of igneous rocks is an obligation owed to the student who really wants to know what geology comprises.

In the new edition there are several notable expansions or changes in treatment. The chapter on the atmosphere has been revised to emphasize

climate and weathering. The erosion cycle is considered more definitely, and new sections treat erosion in semiarid and arid climates. Metamorphism is presented in the modern European fashion. The penultimate chapter on "Land Forms" has been added. Every chapter has a final annotated list of references. Many illustrations are new, and among these are numerous block diagrams and a very few photographs from the air.

Much of the new material is evidence of the growth and integration of the science. For example, the Tokio earthquake is discussed to advantage, and the 35,410-foot Swire Deep is reported (p. 174). The discussion of "Subsurface Water" shows the influence of recent publications on ground water. The much-altered section on geologic deductions from seismograms is very educational to one who has not kept abreast of developments in this field. In the magnificent chapter on "The Origin and History of Mountains" continental drift and other recent hypotheses are mentioned, and the description of Alpine structure is brought up to date, with new figures, though the omission of the map (former Fig. 286) is regrettable. The chapter on the "Nature of the Earth's Interior" contains much new matter and is worth careful reading by anyone, geologist or layman. Among other improvements may be mentioned the discriminating section on the colors of sediments, the modification of Pirsson's attempt at a rough classification of igneous rocks, and the transformation of the chapter on "Ice as a Geological Agent" into a better integrated discussion of "Glaciers and Glaciation."

Of course, every user will find some things that are not entirely satisfactory. After a promising start, there is failure to develop the climatic classification of weathering and soils. Laterite is not even mentioned. Landslides and creep are inadequately treated. More exact data might be given on the rates of weathering and of other geologic processes. Undertow (p. 180) is perhaps described more definitely than the known facts warrant. The discussion of the "shoreline of emergence" (pp. 187–93) places excessive emphasis upon the special coastal-plain conditions shown on the Atlantic side of the United States. The chapter on volcanoes might be bettered by a more leisurely consideration of three or four well-chosen examples. The statement of the elastic-rebound theory (pp. 339–40), though much improved, still lacks a diagram. The final chapter on "Land Forms" is rather one-sided in its emphasis upon water erosion of folded strata. It might be better to transfer here material from other parts of the book, and consider briefly cliffs, valleys, and the like as such, with criteria for the recognition of the various natural associations of such forms.

The principal criticism which the reviewer would offer might be made

in greater or less degree of all existing American and European texts with which he is familiar. The treatment of the various geologic agencies is in the form of a series of descriptive notes, only partially integrated. For example, no text presents in its entirety the fundamental problem of an analysis of physiographic development by stream action, creep, landslip, etc. There is no suggestion that the data for any particular case can be analyzed into "long profile," "cross profiles," and "plan" (which becomes "pattern" when more than one stream line is considered), and each factor (the first two, as well as the third) more or less satisfactorily solved by use of the principles established by Gilbert, Sudry, Walther Penck, Davis, and others.

In recent years books on the principles of chemistry have largely replaced the earlier descriptive texts, and in mineralogy Niggli has achieved something similar. Geology is so varied and complex a subject that our problem is more difficult. Perhaps in 1940 or 1950 it will be possible to set forth adequate *Principles of Geology*. In the meantime, we may take satisfaction as geologists in the existence of so fine a textbook as the new Pirsson.

A. O. WOODFORD

Paleontology. By EDWARD WILBER BERRY. New York and London: McGraw Hill Book Co., 1929. Pp. 392; figs. 175. $3.50.

Paleozoölogy rather than *Paleontology* should be the title of this important textbook, which, paradoxically enough, though written by a distinguished paleobotanist, does not contain a paleobotanic section. As one of the very few American texts dealing entirely with fossils, and indeed the only one to be issued in the last fifteen years, Professor Berry's book is certain to be widely adopted. No higher praise can be accorded the present work than to say that it is very apparently, and quite successfully, modeled after Professor Swinnerton's justly famous English *Outlines of Paleontology*.

In the words of the author, "this book presents a treatment that is, as far as possible, evolutionary and shows adaptions of organisms to their environment." The text is divided into eleven chapters; chapter i is the introduction; chapter v deals with the several phyla generally known as Vermes; and each of the nine remaining chapters is concerned with a single phylum of the animal kingdom. The book is well printed and handsomely bound; it is clearly written, completely indexed, and it contains a carefully selected and valuable glossary.

In spite of the foregoing commendations, Berry's textbook contains a number of features which the reviewer feels are open to criticism. The book contains no acknowledgments, no references, no bibliography, and only a very few text citations of authorities. The introduction makes no mention of the various types of fossils, nor of their modes of preservation. The chapter on the Protozoa gives no hint of their economic importance in the petroleum industry. The chapter on the Porifera is incomplete, that dealing with the Brachiopoda is well written, but scarcely so comprehensive as the paleontologic importance of the group would warrant. A number of the illustrations are original, well chosen, and ably executed; others, such as Figures 26, 31, and 32, are distinctly amateurish; Figures 29, 30, and 31 would be clearer if the parts were labeled; Figure 12 depicts various types of sponge spicules, but fails to indicate which is which; and Figures 153, 156, 166, 173, and 174, showing the past and present distribution of various mammals, are not adequately explained. The chapter dealing with the Vertebrata has an unfortunate subheading entitled Chordata, in which inadvertently *Balanoglossus* is referred to as a worm; and this chapter, comprising 154 pages (in marked contrast to that on the worms with a page and a half) might well have been divided into a chapter for each of the classes discussed. The division dealing with prehistoric man could have been improved by illustrations; and, finally, the book is somewhat uneven in its treatment. For instance, the cephalopods, a class in which Professor Berry is particularly interested, are comprehensively discussed in 26 pages, but the gastropods, less interesting to be sure, are alloted only 5 pages.

A number of other features of this text are at variance with standard usage, a fact for which its author probably should be in the main commended rather than criticized. Sponges are regarded as constituting a separate phylum distinct from the Coelenterata, but the phylum is divided into classes rather than subclasses. Brachiopoda and Bryozoa are discussed as phyla rather than as classes, and the Graptolitoidea are considered as a separate class rather than as an order under Hydrozoa. "Echinoderma" is the term used instead of the more familiar "Echinodermata"; Huxley's term "Discophora" is substituted (inadvisedly, the reviewer feels) for the much better-known "Scyphozoa"; the Trilobita are regarded as a class rather than as a subclass of the Crustacea; and some of Beecher's followers probably will be pained to find that his order Hypoparia has no more standing with Berry than it has with most European students. A great many paleontologists, however, will agree with Berry that "if cephalopods, or other organisms, can have imputed to them any purposes other

than to live and reproduce their kind, then, and then only, is it permissible to speak of modifications . . . . as *degenerate*."

Berry's *Paleontology* is a volume which will be added to the library of every paleontologist, and it will no doubt find a place on the shelves of most general geologic libraries as well.

CAREY CRONEIS

The Major Soil Divisions of the United States. By G. A. WOLFANGER. John Wiley & Sons, 1930. Pp. 150.

This review is written for geologists who have not kept up with some of the recent ideas on soils. In regions of residual soil some of the soil maps show close correspondence with the maps of the geological formations. In other cases the mapping seems to have been done with little reference to the character of the rock from which the soils were derived. This difference seems to be the result of two quite different viewpoints on the influence of rocks on residual soils derived from them.

This book is a radical presentation of the anti-geological viewpoint. It emphasizes the influence of environment and minimizes the influence of the source of the soil. The many references to the publications of the U.S. Bureau of Soils and to various writers on soils might give the reader the impression that these views are generally held by soil authorities.

The author discards previous bases of soil classification—the geologic, the climatic, the botanic, and the topographic. He is particularly emphatic about the geologic. He says: "Groups based upon geologic derivations reveal nothing of importance about the fundamental nature of the soils." He is more sympathetic to the climatic classification but says, "Climate does not account for a number of soil features which are highly important." Regarding native vegetation and topography he says, "Each indicates only indirectly, sometimes incorrectly, its true attributes." In summary he sweeps away all kinds of genetic systems with the statement, "Each is based on factors exterior to the soils."

In place of these he offers: "The only kind of classification appropriate for the type of study here proposed must be attributive in character—one in which the soils' own properties form the basis of grouping. This basis is absolute, not relative, for it describes the soils in exact terms." In the 140 pages of discussion which follow, the concrete-minded reader is apt to be disappointed in the degree of exactness with which soils are described.

In spite of the author's attack on the climatic classification, the distribution of his soil regions is primarily related to climate. For the western

part of the United States his distribution follows precipitation zones and his soil types are largely characterized by the differing percentages of soluble constituents. For Eastern United States his soil belts correspond with temperature belts. These two factors of rainfall and temperature, therefore, seem to be controlling features, but no attention is called to this fact, possibly because these are external phenomena.

This publication emphasizes the soil profile and age relations. Regarding the latter the author says: "Probably the most significant ascertainment of modern soil science is the interpretation that soils pass through cycles of development resembling those of other changing natural phenomena, that is, that there are young, mature, and old soils." Inasmuch as mature soils are defined as those, "which have reached a stage of development marked by the practical absence of geologic features," it is surprising that this topic is treated so briefly.

The writer of this review does not agree with Wolfanger that the attributive classification describes soils in exact terms. On the contrary, it seems to him that soil classification is not exact and that it is a matter of judgment based on rather indefinite characteristics, and finally that soil science has not yet found a suitable basis for classification but is eagerly seeking such a basis.

This publication is to be commended for its emphasis of climatic influences on soils. The writer of this review is much impressed by this idea and feels that this is worthy of detailed study by soil chemists. It is a phase of soil science which has received too little attention. It has geologic as well as "pedalogic" significance. Many geologists are accustomed to regard kaolin as an end product in the belt of weathering. It appears that in the tropics such is not the case—that kaolin, serpentine, and other hydrous silicates lose their silica and the end products are the hydrous oxides of iron and alumina. It is not improbable that the process of laterization is not marked by sharp climatic limits but that it proceeds in decreasing amount with increasing latitude.

R. J. HOLDEN

VIRGINIA POLYTECHNIC INSTITUTE

Introductory Economic Geology. By W. A. TARR. New York: McGraw-Hill Book Co., Inc., 1930. Pp. 664; figs. 249. $5.00.

This book is an outcome of Professor Tarr's long and fruitful experience in the teaching of mineralogy and economic geology at the Univerisity of Missouri. As stated in the Preface, the book is designed for the

elementary student acquainted with only the common minerals and rocks and presumably knowing little of their origins. It is a book which will also be useful to the layman with some slight knowledge of geology. It does not purport to be a critical discussion of the principles of economic geology and does not attempt to refer the reader to original sources of information. It does not, therefore, in any important measure overlap the field of Lindgren's *Mineral Deposits*, issued by the same publishers.

Part I (82 pp.) treats of the history and origin of earth materials, leading—through a brief review of the uses of minerals by primitive man—to an emphasis on their dominant rôle in modern civilization. The larger characteristics of the earth, its dimensions, rigidity, internal pressures and temperatures, and probable zonal arrangements of its materials are briefly discussed. Magmas, their material and the mechanism of differentiation, are also considered. This is followed by a classification of mineral deposits, grouping them into primary and secondary, the primary including (1) syngenetic magmatic deposits, and (2) epigenetic magmatic deposits, and under the latter the usual subdivision into contact metamorphic deposits, pegmatites, deep-seated, intermediate, and shallow veins; and spring deposits of magmatic origin. The secondary mineral deposits are in the main products of weathering and of the transportation and redeposition of weathering products, and the principles involved are adequately expounded.

Part II (250 pp.) is a discussion, seriatim, of the metallic earth materials. The method of treatment may best be illustrated by citing a single example, such as copper. Under that metal its history and the properties of the principal ore minerals are considered; a half-page is devoted to secondary enrichment of copper, and three and a half pages to the methods of treatment of copper ores. These general considerations are followed by a description of the principal producing districts in the United States and foreign countries, four pages being devoted to Butte, two and a half pages to Bingham, and about one page to the important foreign deposits. Uses are rather fully treated in three pages. World production is well shown by maps, graphs, and tables, and the chapter closes with one page of selected reading references.

For the more important resources, full-page maps on Goode's homolosine projection show the location of the world's more important deposits. These constitute a very useful feature of the book.

Part III is devoted to the non-metallic earth materials and occupies 293 pages. Coal is treated first, in 43 pages, and oil and gas in 80 pages. These are followed by a consideration of structural materials, the mate-

rials used chemically, and finally those of miscellaneous uses, such as feldspar, graphite, mica, etc.

The book is a judiciously and carefully organized presentation of the salient facts of occurrence and utilization of our mineral resources. It is illustrated with numerous and well-chosen text figures. It treats more fully than most textbooks in this field the preparation of the raw materials for the market and the uses to which they are applied, and constitutes a very valuable addition to the material at the disposal of the teacher of economic geology.

E. S. BASTIN

Sixteenth Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1927–1928. By GEORGE H. PERKINS. Pp. 390+vi; figs. 63.

Thirteen articles are listed on the title-page and the names of ten authors appear. Many of the studies are of such a nature as to form a valuable contribution to general geology as well as important additions to our knowledge of the geology of Vermont. The Cambrian Paradoxides beds of northwest Vermont, described by B. F. Howell, have long been a puzzle to geologists, and this paper is a splendid summary of present knowledge. A study of rock correlations in west-central Vermont is presented by Edward J. Foyles, together with a table correlating the rocks of this region with those of other parts of the state. Adela M. Pond reports on the peneplains of the Taconic Mountains. Terraces are correlated with those described by Barrell in Massachusetts, but are considered to be of subaerial rather than marine origin. The erosional land forms of eastern and central Vermont are described by Howard A. Meyerhoff and Marion Hubbell. Most prominent are the erosional terraces which are considered to be of fluvial origin. Northern New England is believed to have been raised in a series of uplifts without apparent deformation. Mineral resources for 1928 are given by the state geologist. Granite, marble, and slate are the chief products.

WILFRED TANSLEY

Guide to the Study of Non-metallic Mineral Products (except Building Stones). By W. S. BAYLEY. New York: H. Holt and Co., 1930. Pp. xvi+530; text figs. 127.

Following a chapter on classification are sections on underground water, fuels, salines, gems, abrasives, ceramic materials, cements, fer-

tilizers, and many other materials. The book is comprehensive in the sense that it covers a large number of substances within its field, but of necessity short treatment is given to some of these.

> The purpose of the book is to furnish a basis for a one semester course in the study of the origin and occurrence of the more important non-metallic mineral substances. . . . . It is not intended to cover the subject in a comprehensive way. . . . . It is hoped, however, to familiarize the student with the principal sources to which he may go for further information.

The number of pages devoted to certain subjects follows: petroleum and natural gas, 99; coal, 50; underground water, 31; potash, 21; and phosphates, 20; and fewer pages to all other materials.

Professor Bayley's book is easy to read and contains many references. It is recommended that teachers of the subject carefully examine the book, having in mind its possible adoption for class use.

D. J. F.

Die Entstehung der Mediterran-Roterde (Terra Rossa): Ein Beitrag zur angewandten Kolloidchemie. By P. D. A. A. REIFENBERG. Sonderausgabe aus *Kolloidchemische Beihefte.* Dresden und Leipzig: Steinkopff, 1929. Pp. ix+93; figs. 2.

The author explains the origin of the Mediterranean red earth from colloidal silica. He gives at first a survey of the locality where this red earth is to be found along the Mediterranean, and then discusses the geologic factors and the conditions for the formation of the red earth, especially the existence of colloidal silica, colloidal ferric hydroxide, and colloidal aluminum hydroxide. He adds an extensive bibliography of the subject.

A. C. NOÉ

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